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ARMY RESEARCH LABORATORY

Facility Layout Optimization Tool: Users' Manual

James J. Williams

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FACILITY LAYOUT OPTIMIZATION TOOL: USERS' MANUAL

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September 1996

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13. ABSTRACT *(Maximum 200 words)*

The facility layout optimization tool (FLOT) is interactive software designed to assist in the evaluation and design of facility layouts. It consists of two programs. The first, the facility layout tool (FLAYOUT), is used to model the physical structure, the interior walls, and the workstation positions in a two-dimensional plane. The second program, the facility optimization tool (FOPT), is used to solve the problem of arranging work stations within a facility in a way that will minimize interaction costs (e.g., human travel distance, paper flow, material handling, etc.). This users' manual contains installation instructions, a tutorial, a technical discussion section, an appendix devoted to the optimization problem, and the software on a DOS-formatted 3.5-inch diskette. FLOT operation requires at least 4 megabytes of extended memory. Executable files of the two programs are provided for users with DOS-based personal computers. Users on other systems will need access to a FORTRAN 77 compiler.

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CONTENTS

FIGURES

TABLE

EXECUTIVE SUMMARY

Requirement

The Fort Hood and Fort Sill Field Elements, Human Research and Engineering Directorate of the U.S. Army Research Laboratory (ARL), in cooperation with the Army Research Institute, Fort Leavenworth Field Unit, developed the facility layout optimization tool (FLOT) to support a program aimed at optimizing facility and command post design. The constraints on this tool were that it should be transportable, flexible, and allow researchers and users to model facilities of various sizes (5 to 100 work stations).

Procedure

The interactive software developed consists of two programs. The first, the facility layout tool (FLAYOUT), is used to model the physical structure, the interior walls, and the workstation positions in a two dimensional plane. The second program, the facility optimization tool (FOPT), is used to solve the problem of arranging work stations within a facility in a way that will minimize interaction costs (e.g., human travel distance, paper flow, material handling, etc.). This problem is known as a quadratic assignment (QA) problem. The only procedures for precisely solving QA problems are implicit enumeration algorithms, which limit the size of problems to be solved. In FOPT, this limit is 12 workstations. To solve large QA problems, heuristic (decision rule) procedures were used. The software is programmed in standard FORTRAN 77.

Findings

This user's manual contains installation instructions, a tutorial, a detailed technical discussion section, and appendices that explain the QA problem and the solution approaches to that problem. The FLOT programs require at least 4 megabytes of memory. Users on an IBM-compatible personal computer (PC) must have at least a 386, 4 megabytes of extended memory, and the disk operating system (DOS) 5.0. Upgrades from these minimum requirements are acceptable. The software is supplied as executable files for the PC user and as FORTRAN source code for users of other systems.

Use of Findings

FLOT is designed for human factors engineers, research psychologists, operations analysts, and facility planners. Typical users will be individuals involved in the design and evaluation of a facility layout.

FACILITY LAYOUT OPTIMIZATION TOOL: USERS' MANUAL

OVERVIEW

Introduction

The facility layout optimization tool (FLOT) is interactive software that can assist users in generating and evaluating alternate facility layouts. FLOT can be used to arrange departments, personnel, equipment, or workstations in a facility. FLOT was originally developed to model the physical relationships that exist when executing command and control functions in a command post environment.

Generating and ranking alternate layouts are critical steps in the facilities planning process (Tompkins & White, 1984). The approach employed in this modeling tool is to evaluate the physical arrangements in a facility and to generate improved facility arrangements, based on the quality of interaction between elements in the facility. The quality of interaction is improved by decreasing the total cost of interaction in the facility. The cost of interaction between two elements (hereafter referred to as workstations) is the multiplication of the distance and the weight between the workstations. The weight of interaction between two workstations can be the frequency of personnel or machine interactions or the quantity of paper or material flow. These weights can also be combined with priority or the ability to communicate.

Workstations are artificially represented as 3-inch squares in this version of FLOT (each character or space in the model represents a 3-inch square). Representing workstations in this manner is useful for modeling relationships between workstations and for modeling large facility layouts or command post arrangements, because models can be formulated and run quickly. The workstation arrangements modeled in and generated by FLOT are not intended to be precise solutions. However, the evaluations and arrangements produced by FLOT are alternate arrangements that provide information useful to facility layout designers and evaluators.

FLOT users must be able to copy, delete, rename, and edit files using the operating system of the computer being used. Typical users will be involved in the design and evaluation of a facility layout. A human factors engineer, a research psychologist, an operations analyst, and a facility planner could use information produced by FLOT.

Software

FLOT contains two FORTRAN programs that require at least 4 megabytes of free (available) random access memory (RAM) to be executed. In an IBM-compatible personal computer (PC), at least 4 megabytes of extended memory are required. The PC should also be a 386 or better and have the disk operating system (DOS) 5.0 or higher. Executable files of the FORTRAN programs and a DOS-extender file are provided for PC users. The DOS-extender file must be present for the program executable files to run. The FORTRAN source code, which can be compiled with any standard FORTRAN 77 compiler, is provided for users on other systems or for the aggressive analyst who wishes to modify the source code. Instructions for probable source code modifications are provided in the *Design Limitations* sections on pages 35 and 46.

The first program, the facility layout tool (FLAYOUT), requires a two-dimensional model of a facility with the exterior structure, interior walls, and positions of workstations. The user can either construct a model of a facility or use portions of models constructed earlier. FLAYOUT will then calculate the distance among all workstations in the model. Workstations can be personnel, equipment, or even whole departments in larger facilities. By analyzing distances and relationships between workstations, alternate arrangements of workstations may become apparent.

The second program, the facility optimization tool (FOPT), requires a cost (weight) matrix containing the weight of interaction between all pairs of workstations. The user can either enter the weights one at a time as the program prompts the user or have the weights already entered in a data file that the program will read. The input data file format is listed in the *Weight Matrix* section on page 45. The FOPT then formulates the facility layout as a quadratic assignment (QA) problem, evaluates the current arrangement, and generates and evaluates new improved arrangements. The QA problem is to assign n workstations into n locations to minimize the sum of inter-workstation interaction costs (see Appendix A for the mathematical description). The interaction cost between two workstations is the weight of interaction multiplied by the distance between the two workstations. Computationaliy, the QA problem is difficult to solve, particularly for large problems (when $n > 12$). For this reason, seven heuristic algorithms and a starting solution generator are available in the FOPT. More information about the solution algorithms is available in the *Optimization Algorithms* section beginning on page 47 and in Appendix B.

How to Use This Manual

The remainder of this manual is divided into five sections and two appendices. The first section, *GETTING STARTED,* should be consulted by first time users. It restates the computer requirements needed to run the FLOT programs and lists the files that should be uploaded from the FLOT diskette.

Next, the new user should follow the *TUTORIAL* in its entirety. In the first part of the *TUTORIAL,* the user will run both FLOT programs, FLAYOUT and FOPT, using an existing model of a command post for an armor or mechanized infantry battalion task force and then analyze the results. In the second part, the user will construct, from scratch, a facility layout using the FLAYOUT program and then enter a weight matrix and evaluate and rearrange the workstations using the FOPT program. New users should then read the *ANALYZE RESULTS* section for more detail about analysis techniques.

The *TECHNICAL DISCUSSION* section should be consulted to assist users with specific questions about FLOT operations, applications, or modifications. The *ERROR MESSAGES* section should be consulted when confusion exists regarding error messages. Each error message produced by either the FLAYOUT or FOPT programs is explained and courses of action are recommended. Probable causes of system errors are also presented.

Listed in the *Optimization Algorithms* section beginning on page 47 are the solution algorithms available in the FOPT to solve the QA problem. Appendix A presents the mathematical description of the QA problem. Appendix B describes these algorithms in greater detail and presents a study comparing the algorithms.

Most command instructions in this manual will be on two lines. The first line, in all capital letters, is a prompt that the program will display on the terminal screen. The second line is the response the users should enter. All commands in this manual that the user should enter into the computer are presented in **bold**. Indented paragraphs or instructions following a program prompt should be read before responding to the prompt. Specific file names are also presented in **bold**.

GETTING STARTED

The FLOT version 2.0 is FORTRAN-based software. The software contains two FORTRAN programs **FLAYOUT.FOR** and **FOPT.FOR**. These programs are provided as FORTRAN 77 source code. They require at least 4 megabytes of available or free RAM to run. The files **FLAYOUT.EXE** and **FOPT.EXE** are executable files (compiled FORTRAN programs) for an IBM-compatible PC. PC users should have a 386 or higher version computer, at least 4 megabytes of extended memory, and DOS 5.0 or higher. Users of systems other than PCs will require access to a FORTRAN 77 compiler.

Upload Files

Copy (upload) the following files from the 3-inch disk to a directory or disk from which you are planning to operate:

FORTRAN source codes for the FLOT programs

FLAYOUT.FOR	-	The first program in FLOT
FOPT.FOR	-	The second program in FLOT

Executable programs for MS-DOS-based IBM-compatible PCs

FLAYOUT.EXE	-	The first program in FLOT
FOPT.EXE	-	The second program in FLOT
RUN386.EXE	-	A DOS-extender file

*** The DOS-extender file is required to execute the executable program files. It must be present in the current operating directory or in a directory that is on the "path" statement of the "autoexec.bat" file.

Following are data files that will be used during the tutorial. These files must be renamed before executing the FLOT programs. See the *Tutorial* section, pages 9, 15, and 31, for instructions.

FLIP.4
FLIP1.7
FLIP2.7
FLIP-1.15
FLIP 2.15

CP-9.4
CP-9.7
CP-9.15

TUTORIAL

This tutorial is meant to be completed sequentially and in its entirety. First, you will run a sample model and analyze the results. Then you will construct a facility layout, enter the weight of interaction data, and analyze the results.

Run an Existing Model

Set Up Input Files

The Infantry School developed a command post configuration of M577 armored personnel carriers for adoption as the Army-wide Functional Command Post for the Armor and Mechanized Infantry Battalion Task Forces (Michel & Fallesen, 1990). To access a representation of this model enter the following copy commands:

1) **COPY FLIP.4 WALLS.4**

WALLS.4 is the new input file. It contains data needed to construct the physical structure, including walls and numbers (names) of all the 3-inch square cells within the facility that do not contain a wall.

2) **COPY FLIP1.7 STATION.7**

STATION.7 is the new file. It contains the location and names of workstations within the facility.

3) **COPY FLIP-1.15 FREQDATA.15**

FREQDATA.15 is the new file. It contains the weight of interaction data (the weight of the interactions between all pairs of workstations).

Start FLAYOUT

At your system prompt

Enter **FLAYOUT.** This entry can be either upper or lower case.

> Note. You can exit or quit the program by entering '99999' (five nines) in response to any question.

The program will ask

ARE YOU USING AN EXISTING FACILITY STRUCTURE (Y,N)?

Enter **Y**

> You accessed an existing facility structure (WALLS.4) with the previous copy commands.

Then the program will ask

ARE YOU USING AN EXISTING WORKSTATION DATA SET (Y,N)?

Enter **Y**

> You accessed an existing workstation data set (STATION.7) with the previous copy commands.

Then the program will ask

DO YOU WANT TO VIEW THE FACILITY LAYOUT (Y,N)?

Enter **Y**

> The display you are viewing is the facility layout. Its representation in the program has been reduced to fit the terminal screen. The "Zs" define the outside border of the facility, the other letters define walls or partitions in the layout, and the numbers define workstation names and locations.
>
> The "@" symbol is displayed where more than one type of character occupies (shares) the same space in the reduced display. Note. This usually occurs at intersections of walls, when a workstation has more than a one-character name, when a workstation is fixed, or when a workstation is placed within 1 foot of a wall or another workstation. Occasionally, as

in this case, the entire south or east wall is represented by "@s." This sometimes happens when the facility must be reduced two or more times to fit the terminal screen.

When the system prompt re-appears, the FLAYOUT program has finished.

FLAYOUT generated numerous files. Among them are two files useful for preliminary analysis, LAYOUT.8 and DISTANCE.12. The use of these files is discussed later.

Start FOPT

At your system prompt

Enter **FOPT**

The program will ask

ARE YOU USING AN EXISTING WEIGHT DATA SET (Y,N)?

Enter **Y**

You accessed an existing weight data set (FREQDATA.15) with the previous copy commands.

Then the program will ask

DO YOU WANT TO SELECT THE SOLUTION PROCEDURE (Y,N)?

Enter **N**

The program will select an algorithm to solve the problem, based on the problem size. In this case, Enumeration is selected.

Then the program will ask

HOW MANY OF THE TOP SOLUTIONS DO YOU WANT?

Enter **20**

The program will now start the Enumeration algorithm. Enumeration requires more computer time than any of the other algorithms. However, this problem should be solved quickly.

When the system prompt returns, the FOPT program has finished.

FOPT generated BEST.20 as a results file.

Analyze the Results File

1) Obtain a hard copy (printout) of **BEST.20**.

2) The printout displays the original cost and the associated arrangement of workstations, the worst cost and the associated arrangement of workstations, the best cost and the associated arrangement of workstations, and as many of the top solutions (best alternatives) as you requested. Better solutions (arrangements) have lower costs.

The computer reads the workstations from left to right, top to bottom, in the same fashion as we would read a page of text material.

The "cost" of an arrangement is the sum of the multiplications of the weight of interaction (contained in FREQDATA.15) between two workstations and the distance between the two locations, for all pairs of workstations. In this model, there are eight workstations (n=8) making 28 pairs of workstations (n(n-1)/2).

Look at the workstation arrangements on the hard copy of BEST.20. The columns of the arrangements refer to locations of workstations in the facility layout. These columns are in the order the computer reads the workstations. For example,

> in the original arrangement, workstation 1 is in location 1,
> in the worst arrangement, workstation 3 is in location 1, and
> in the best arrangement, workstation 7 is in location 1.
>
> Also, in the original arrangement, workstation 8 is in location 3; in the worst arrangement, workstation 6 is in location 3; and in the best arrangement, workstation 1 is in location 3.

3) To save this result, BEST.20 must be copied to another file name (or renamed). Otherwise, BEST.20 will be replaced the next time FOPT is executed.

COPY BEST.20 New filename

Use Heuristics

Other solution procedures are available to solve this problem. Enumeration, the algorithm just used, is the only algorithm that will always find the optimal answer. The problem with Enumeration is that it can only be used to solve small problems (number of workstations fewer than 12). For larger problems, heuristic (decision rule) procedures must be used. Seven heuristics are available in FOPT.

The heuristics available in FLOT repeatedly make workstation location changes that improve a solution. None of the heuristics will always reach solutions superior to solutions reached by other heuristic algorithms. Each heuristic is capable of finding a solution superior to that found by the other heuristics. For this reason, the user solving a large problem should use as many different heuristics as possible for the analysis.

See the *Optimization Algorithms* section, beginning on page 47, for more information.

To use another solution algorithm begin at the system prompt.

Enter FOPT

The program will ask

ARE YOU USING AN EXISTING WEIGHT DATA SET (Y,N)?

Enter Y

Then the program will ask

DO YOU WANT TO SELECT THE SOLUTION PROCEDURE (Y,N)?

Enter Y

The program will ask

WHICH OPTIMIZATION PROCEDURE SHOULD BE USED?

It will then display the list of available algorithms.

Select any of the algorithms by entering the letter that appears to the right of the title.

After one of the heuristics solves the problem, the program will ask

HOW MANY ADDITIONAL STARTING ARRANGEMENTS SHOULD BE RUN?

ENTER A NUMBER FROM 0 TO 100.

> When this prompt appears, the program has solved the problem using the heuristic you selected and the original arrangement as the starting arrangement. Now the program is offering to generate additional starting arrangements and solve them with the heuristic you selected.
>
> The heuristics will find different final solutions, depending on the starting solution. This feature of FLOT is very useful for finding better or even the best solutions to large problems.

If you enter a number greater than **0**, the program will instruct you to

ENTER A SEED NUMBER FOR RANDOM SOLUTION GENERATOR

Enter **any whole number** - the random solution generator works best when an odd number with five or more digits is entered.

Then the program will ask

HOW MANY OF THE TOP SOLUTIONS DO YOU WANT?

Enter any number between **1** and **100**.

> Note. Each run of a starting arrangement will save at most, the top five arrangements (solutions). If you asked for three additional starting arrangements (in addition to the original arrangement, 3 + 1 = 4) to be run and 20 of the top solutions (four problems to be solved, multiplied by five top solutions being saved from each), expect less than 20 solutions to be stored in BEST.20. The program will only save unique solutions.

If you do not want any additional problems solved,

Enter **0** in response to:

HOW MANY ADDITIONAL STARTING ARRANGEMENTS SHOULD BE RUN?

The program is complete when the system prompt returns.

To analyze the results, repeat the instructions from the section *Analyze the Results File*, page 12.

Run an Additional Model

Another model of the command post for the armor and mechanized infantry battalion task force (Michel & Fallesen, 1990) is available for additional practice. It can be accessed by entering the following copy commands and then following the program execution procedures that began on page 10.

1) **COPY FLIP2.7 STATION.7**

2) **COPY FLIP-2.15 FREQDATA.15**

The model that was set up on page 9 uses the same **WALLS.4** file that is required to run this model. Therefore, copying **FLIP.4** to **WALLS.4** should not be necessary.

This concludes the first section of the tutorial. After becoming familiar with running existing models, you should proceed to the next section, in which you will construct a facility.

Construct a Facility

In this section, you will build a facility using FLOT. In the first program (FLAYOUT), you will 1) build the structure of a facility and 2) enter the workstation locations. In the next program (FOPT), you will 1) enter the interaction data, the weights describing relationships among all pairs of workstations and 2) select a solution procedure to improve the arrangement of the workstations within the facility.

FLAYOUT

Before beginning, you should have a diagram of the facility to be modeled.

Use Figure 1 for this tutorial.

Begin FLOT at the system prompt.

Enter FLAYOUT

Note. You can exit or quit the program by entering '99999' (five nines) in response to any question.

Facility Structure

The program will ask

ARE YOU USING AN EXISTING FACILITY STRUCTURE (Y,N)?

Enter N

Figure 1 is a diagram of a notional battalion command post structure. This command post is 30 feet 0 inches long (left to right) by 30 feet 0 inches wide (top to bottom).

BUILD INSIDE DIMENSIONS OF OUTER WALLS OF THE FACILITY. THE DIMENSIONS ARE LIMITED TO 75 FEET IN LENGTH AND 75 FEET IN WIDTH WITH THE TOTAL AREA NOT EXCEEDING 2,000 SQUARE FEET.

ENTER LENGTH OF FACILITY (# OF FEET SPACE # OF INCHES)

Enter 30 0

ENTER WIDTH OF FACILITY (# OF FEET SPACE # OF INCHES)

Enter 30 0

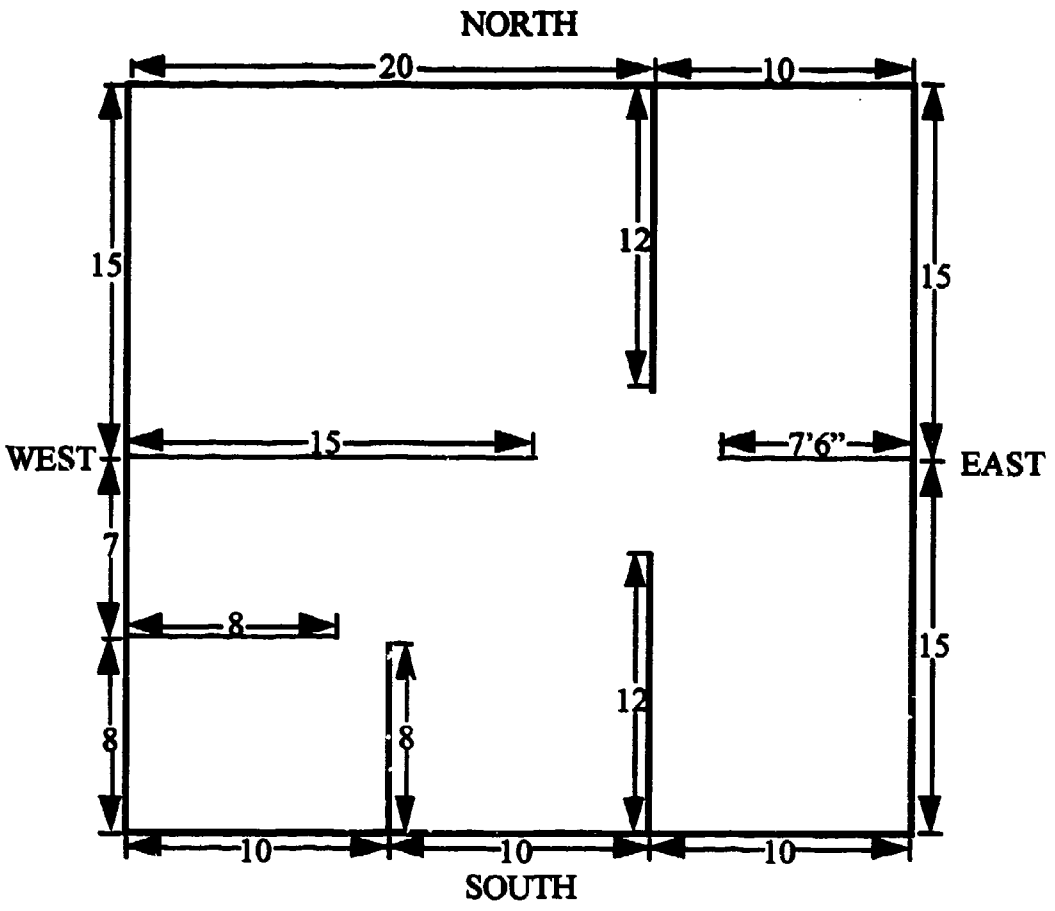

Figure 1. The structure of a notional battalion command post.

You will now be asked to construct the interior walls of the facility. The program will start in the northwest (top left) corner and move clockwise around the outer edges, asking if walls extend into the facility from the outer walls.

The program will tell you the current position (that position from which all measurements will be taken) before asking for the distance to a wall. The program will also tell you every time the current position is changed.

THE OUTSIDE WALLS ARE INCLUDED ALREADY. ENTER THE INSIDE WALLS. ASSUME THAT UP IS NORTH AND RIGHT IS EAST. CURRENT POSITION IS THE NORTHWEST (TOP LEFT) CORNER. DOES ANOTHER INSIDE WALL INTERSECT THE NORTH WALL (Y,N)?

Enter **Y**

ENTER DISTANCE TO WALL, FROM THE CURRENT POSITION ON THE NORTH WALL?

Enter **20 0**

ENTER LENGTH OF WALL (FEET SPACE INCHES)?

Enter **12 0**

DOES ANOTHER INSIDE WALL INTERSECT THE NORTH WALL (Y,N)?

Enter **N**

Follow the instructions displayed on your screen and finish constructing the interior of the facility, as given in Figure 1. Pay close attention to the current position when entering the second wall on the south and west walls.

After entering all the interior walls, the program creates WALLS.4. WALLS.4 contains the facility structure and the names of every 3-inch square cell in the facility.

Note. If needed, you can exit or quit the program by entering '99999' in response to any question. If you have finished entering the structure (frame and all interior walls) before you exit the program, the structure will be saved to WALLS.4.

To restart the program without re-entering (constructing over again) the facility structure, begin at the system prompt.

Enter **FLAYOUT**

The program will then ask

ARE YOU USING AN EXISTING FACILITY STRUCTURE (Y,N)?

Enter **Y**

Workstations

After the interior walls are constructed, the program will ask

ARE YOU USING AN EXISTING WORKSTATION DATA SET (Y,N)?

Enter N

In this section, the location and status of workstations will be entered. Figure 2 displays the workstations within the facility you are constructing.

The program will then ask

DO YOU WANT TO VIEW THE FACILITY LAYOUT (Y,N)?

Enter Y

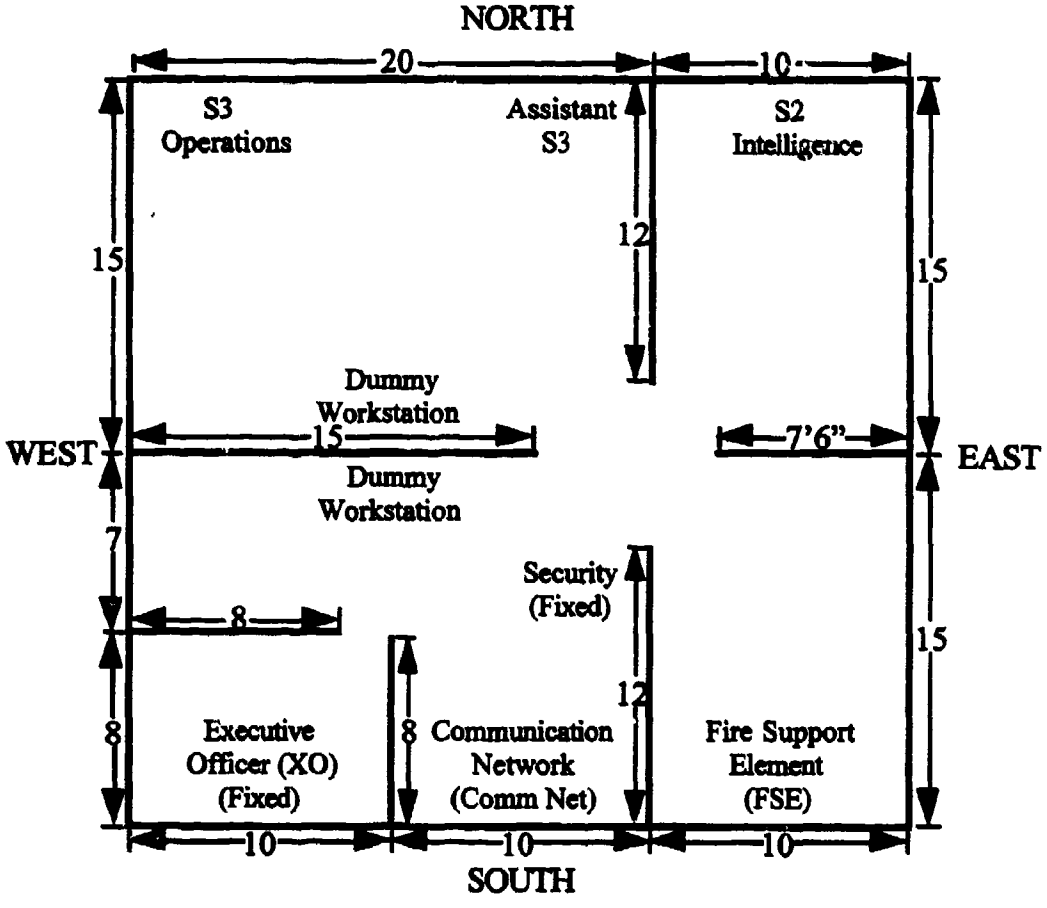

Figure 2. Arrangement of work stations in the notional battalion command post.

The program will display the facility layout to your terminal screen after you enter **Y**. Copy the letter names of the walls from your terminal screen to your diagram (Figure 2). The program display is a reduced structure (containing only the walls) of the facility that you are constructing. The outside edge of the facility is represented by "Zs" and each wall is represented by the wall's name (one letter) being repeated.

Some computer systems will display the facility layout for only 2 minutes. If you missed the opportunity to write the letter names of the walls on Figure 2 you can

1) Start in the northwest corner of Figure 2 and label the interior walls in a clockwise rotation sequence. The first interior wall will be named **A**, the next **B**, and so on through **F**.

or

2) Exit the program by entering '99999' in response to the next question. Then at the system prompt, start again.

Enter **FLAYOUT**

The program will ask

ARE YOU USING AN EXISTING FACILITY STRUCTURE (Y,N)?

Enter Y

The program will then ask

ARE YOU USING AN EXISTING WORKSTATION DATA SET (Y,N)

Enter N

The program will then ask

DO YOU WANT TO VIEW THE FACILITY LAYOUT (Y,N)?

Enter Y

And write the letter names of the walls on Figure 2.

After displaying the reduced layout, the program will ask

ENTER WORKSTATION LOCATIONS
STARTING CURRENT POSITION IS THE NORTHWEST CORNER

IS THERE A STATION(S) IN THE SPACE IN FRONT OF THE NORTH WALL BEFORE WALL A NOT ALREADY ENTERED (Y,N)?

Read this section before entering Y:

You are going to enter the workstations in this portion of FLAYOUT. The following are instructions necessary for entering workstations.

The program will tell you the current position before asking for the location of each workstation.

Suggestion: For easier viewing of the layout, enter workstations at least 1 foot away from walls and other workstations; also make workstations along a wall the same distance from the wall.

The program will ask if a workstation should be "fixed to this location." *Fix the location (answer Y to the question) of the security and executive officer only. All other workstations should not be fixed (answer N to the question).* The next program (FOPT) will rearrange workstations based on interaction and distance between workstations. The fixed workstations will have an influence on the location of other workstations, but they will remain in their original location (as you entered them).

The "Dummy Workstations" in Figure 2 are candidate workstation locations, that currently are vacant space. At this time, just enter their location and do not fix them to the location.

If you notice an error immediately while entering the data for a workstation, you can recover. When asked to enter the distance in either direction from the current position, enter a distance that is greater than the size of the facility being modeled (99 0). The program will tell you an error has been made and will erase the data for the workstation you are entering. It will then repeat the question before you enter data for the workstation.

If the current position has moved past a location you wanted for a workstation, you can recover. You can enter any workstation in front of a current position, regardless if interior walls are between the current position and the location of the workstation.

Example: If your current position is the corner of the North wall and wall A (the only interior wall connected to the north wall) and you missed entering the Assistant S3 before wall A,

You can continue and enter the rest of the workstations in front of the North wall after wall A.

Then, when your current position has moved to the corner of the North wall and the East wall, you can enter the workstation you missed before wall A. Be careful to calculate the proper distances from the current position to the workstation. The distance in the north-south direction will be approximately 2 feet and in the east-west direction approximately 12 feet (10 feet to wall A + 2 feet past wall A).

Note. The workstation entered out of sequence will have a program assigned--name also out of sequence.

If you made other workstation entry errors, do not worry. They can be corrected after the program has completed. Finish entering the rest of the workstations as if you did not make an error. The details for correcting the workstation errors are discussed later in the *Correct The Workstation Data Set* section, page 23.

Note. The actual locations of each workstation are not given to you, forcing you to increase your powers of estimation, at the same time becoming more familiar with FLOT.

Enter Y

and follow the instructions and questions displayed on the screen. Continue on your own until all the workstations are entered.

Once all the workstations are entered, the program creates STATION.7, the workstation data set, and LAYOUT.8, the facility layout.

View the Facility

The program will then ask

DO YOU WANT TO VIEW THE FACILITY LAYOUT (Y,N)?

Read this section before entering Y:

Look at Figure 2 and look at the facility displayed on your terminal screen after you enter Y. Copy the numbers (program-assigned

workstation names) of the workstations from the facility display on your terminal screen over the workstation names in Figure 2.

Enter **Y**

If you missed the opportunity to write the numbers (program-assigned workstation names) of the workstations over the workstation names in Figure 2, you can obtain the numbers (program names) of the workstations from **LAYOUT.8**.

The program then calculates the distance between each pair of workstations and generates DISTANCE.12 and NUMSTAT.13 for use in FOPT.

The program is finished when the system prompt returns.

Correct the Workstation Data Set

If you observed an error when you entered the workstation data, you do not have to re-enter all the data to correct the mistake.

1) Obtain a hard copy of **LAYOUT.8**:

Note. Most line printers are limited to 133 characters per line. If the facility being modeled is longer than 33 feet in the east-west direction, a hard copy printout of the facility will not contain the entire facility. The unprintable portion, however, can be observed in a text editor. The command post being modeled in this tutorial can be printed in its entirety.

LAYOUT.8 contains the unreduced physical structure and workstation arrangement. The representation of the layout will seem too wide (north-south direction) because each character space represents a square cell; however, each character is displayed taller than it is wide.

2) Analyze the facility layout.

Analyze the position of workstations in the layout (LAYOUT.8). Select the modifications needed to correctly model the workstation arrangement. Make estimates for the distances that workstations need to be moved or the distances, from the top and left side, to locations where workstations are to be added.

Note. The workstation data set is in STATION.7. You are analyzing and gathering measurements from LAYOUT.8 to enable

you to modify the workstation data set (STATION.7), because the workstation data set contains only the workstations and no points of reference, such as interior walls.

3) Change workstation data set.

a) To move a workstation

1) Enter STATION.7 into a text editor.

2) Move your cursor to the workstation to be moved.

3) Move the cursor the appropriate spaces (1 space represents 3 inches) to the new location of the workstation.

4) Enter the workstation name (number or letter, program name).

5) Return the cursor to the original position of the workstation, and erase the workstation from the original location.

b) To add a workstation:

1) Enter STATION.7 into a text editor. The top line of STATION.7 displays the dimensions of the facility in units (10 units = 3 inches = 1 character space or 1 vertical line).

2) Realizing the top line is not part of the facility and that the north wall occupies 3 inches (another line), move the cursor down the appropriate number of lines to the horizontal level of the new workstation.

3) Realizing the first character is always blank to avoid confusion with certain line printers and the west wall occupies 3 inches (accounting for two spaces), move the cursor horizontally to the location of the workstation to be added.

4) Add the name (number or letter, program name) of the new workstation. The name of the new workstation cannot be the same as one of the other workstations.

Workstation Names (program names) can be one or two characters. If the name is one character it can be any digit or capitalized alphabetic character. If the name is two characters the first must be a capitalized alphabetic character and the second must be a digit.

c) To fix or free a workstation

1) Enter STATION.7 into a text editor.

2) Move the cursor to the workstation.

3) To fix the workstation, add the ^ symbol (shift 6) next to the workstation. Directly in front (to the left) of the workstation is the preferred position. However, if the workstation is next to a wall or close to other workstations, other positions for the ^ symbol must be found. The ^ symbol can be placed above or below the first character in the workstation name, or in the second space behind (to the right of) the first character of the workstation name. Analyze LAYOUT.8 to determine if other positions other than in front of the workstation must be used for placement of the ^ symbol.

To free a workstation, simply erase the ^ symbol that is next to the workstation.

4) Run FLAYOUT after changing the locations of workstations (in STATION.7). This will produce the correct data input files for the next program (FOPT).

Begin at the system prompt:

Enter **FLAYOUT**

The program will ask

ARE YOU USING AN EXISTING FACILITY STRUCTURE (Y,N)?

Enter **Y**

Then the program will ask

ARE YOU USING AN EXISTING WORKSTATION DATA SET (Y,N)?

Enter **Y**

Then the program will ask

DO YOU WANT TO VIEW THE FACILITY LAYOUT (Y,N)?

Enter **Y**

And check if the workstation placements are correct.

FOPT

When you are satisfied with the facility layout, begin the FOPT. BE SURE to always run FLAYOUT after changing the locations of workstations (see pages 10 and 25).

At the system prompt

Enter **FOPT**

Note. You can exit or quit the program by entering '99999' (five nines) in response to any question, except 'ENTER A SEED NUMBER FOR RANDOM SOLUTION GENERATOR'.

Weight Data Set

The program will ask

ARE YOU USING AN EXISTING WEIGHT DATA SET (Y,N)?

Enter N

Because you are going to enter the weight data set.

The program will respond

THE 9 STATIONS ARE IN THE FOLLOWING ORDER
1 2 3 9 8 5 7 6 4
ENTER THE WEIGHT OF INTERACTION AMONG THE VARIOUS STATIONS.
WEIGHT OF INTERACTION DATA IS LIMITED TO 3 DIGITS PER ENTRY.

ENTER THE WEIGHT OF INTERACTION BETWEEN STATIONS 1 AND 2.

The program displays the order that it reads the workstations. Your workstation numbering may be different, depending on the order in which you entered the workstations and the actual position of the workstations. The program will then ask for the "WEIGHT OF INTERACTION" between the first workstation and the next. Enter the **whole numbers** from the appropriate rows and columns of **Table 1** in response to questions from the program.

Write the appropriate names (program-assigned names) of the workstations (from Figure 2, which you modified by entering the workstation numbers at the end of FLAYOUT) above the columns and beside the rows in Table 1. Table 1 contains the weight of interaction data. For this tutorial, consider the weight of interaction data to be the average

number of face-to-face communications between personnel at each workstation. When modeling real problems, these data will be gathered through observations or calculations.

Solution Procedure

After entering the weight of interaction (relationship) information, the program will ask

DO YOU WANT TO SELECT THE SOLUTION PROCEDURE (Y,N)?

1) If you **enter** N, the program will select Enumeration (since n = 9).

The program will then ask

HOW MANY OF THE TOP SOLUTIONS DO YOU WANT?

Table 1

Weight of Interaction Among Staff Elements (Workstations) in the Notional Battalion Command Post

ELEMENTS	S3	Asst S3	S2	Dummy	Dummy	Security	XO	Comm Net	FSE
S3	**0**	30	20	0	0	2	25	15	10
Asst S3		**0**	10	0	0	9	12	7	5
S2			**0**	0	0	1	28	20	12
Dummy				**0**	0	0	0	0	0
Dummy					**0**	0	0	0	0
Security						**0**	2	0	1
XO							**0**	30	15
Comm Net								**0**	10
FSE									**0**

Note. The dummy workstations are candidate workstation locations and not actual workstations (i.e., physical locations to which any non-fixed staff element might be assigned in the optimal solution). These dummy workstations have zero interaction with all other workstations.

Enter any whole number between 1 and **100**.

Notice that this 9 workstation problem requires less computer time than the 8 workstation problem you ran in the first part of this tutorial. The reason is that two of the workstations, those for the security and the executive officer, are fixed to their location, requiring Enumeration to only explore 7 factorial (7!) different arrangements; the 8 workstation problem solved earlier required Enumeration to explore 8 factorial (8!) different arrangements.

The Enumeration algorithm is limited to 12 workstation problems. However, problems with more than 9 free-to-move (not fixed) workstations should not be attempted by Enumeration, because of the immense amount of computer time required.

2) If you **enter** Y, the program will ask

WHICH OPTIMIZATION PROCEDURE SHOULD BE USED?

and will display the list of available algorithms.

Select any of the algorithms.

For information about the algorithms, see the *Optimization Algorithms* section, page 47, or Appendices A and B.

After the problem is solved by one of the heuristics (any available algorithm except Enumeration), the program will ask

HOW MANY ADDITIONAL STARTING ARRANGEMENTS
SHOULD BE RUN?
ENTER A NUMBER FROM 0 TO 100.

When this question is asked, the program has solved the original problem you set up, with the heuristic you selected. The program is offering to generate additional starting arrangements and solve them with the algorithm you selected.

The heuristics will find different final solutions, depending on the starting solution. This feature of FLOT is very useful for solving large problems that an exact solution procedure cannot solve. However, in this case with only seven workstations being free to move, most starting arrangements will enable the heuristics to find the optimal solution.

Enter a number greater than 0 for the program to generate and solve alternate arrangements. The program will then ask

ENTER A SEED NUMBER FOR RANDOM SOLUTION GENERATOR

Enter any whole number - the random solution generator works best when an odd number with five or more digits is entered.

Then the program will ask

HOW MANY OF THE TOP SOLUTIONS DO YOU WANT?

Enter any whole number between 1 and **100**.

> Note. Each run of a starting arrangement will save, at most the top five arrangements (solutions). If you asked for three additional starting arrangements (in addition to the original arrangement, 3 + 1 = 4) to be run and 20 of the top solutions (four problems to be solved multiplied by five top solutions being saved from each), expect fewer than 20 solutions to be stored in BEST.20. The program will only write unique solutions to BEST.20.

The program will then ask

HOW MANY ADDITIONAL STARTING ARRANGEMENTS SHOULD BE RUN?
ENTER A NUMBER FROM 0 TO 100.

Enter 0, if you do not want any additional problems solved.

The program will create the results file (**BEST.20**) and stop, returning you to the system prompt.

Interpret Results

Obtain a hard copy of **BEST.20**.

By observing the location of each workstation in LAYOUT.8 or Figure 2 and the column that each workstation is listed in the original arrangement (found in BEST.20), you can determine the position that corresponds to each column. The position of workstations in the facility layout corresponds to the column that the workstation program name is displayed in the original arrangement. Each column of all the displayed arrangements corresponds to a position in the facility layout.

In the original arrangement, an "F" will be displayed behind a workstation that is fixed to its location. In each arrangement generated by the program, a fixed workstation should be displayed in the same column.

The names displayed in each column are the names of the workstations that occupy each position or location in the various arrangements. If workstation 2 is in the first column of the best arrangement and you had constructed the facility with workstation 1 in the first position (column) of the original arrangement, you should write workstation 2 into the position that workstation 1 occupied in the original arrangement (see Figure 2). Write the workstation names from the best arrangement in BEST.20 into the appropriate positions in Figure 2.

Save Model

To save the model you just created, you should copy to another file name or rename the input files. The input files are

WALLS.4
STATION.7
FREQDATA.15

If these input files are not renamed, they will be replaced when new r. . lels are created.

To save the results file, you should copy to another file name or rename the results file (BEST.20). If the results file is not renamed, it will be replaced the next time FOPT is executed.

Author's Solution

In the author's solution, the optimal arrangement of workstations in the notio. .attalion CP has a cost of 195,734 with workstations located as displayed in Figure 3. Your r. . .lts (BEST.20), particularly the cost of the solution, may vary slightly. The differences are probably caused by workstation locations being slightly different between your model and the CP-9 m del, as you were not supplied precise locations for the workstations.

To access the author's solution, copy the following data files (the CP-9 model) to the appropriate input files.

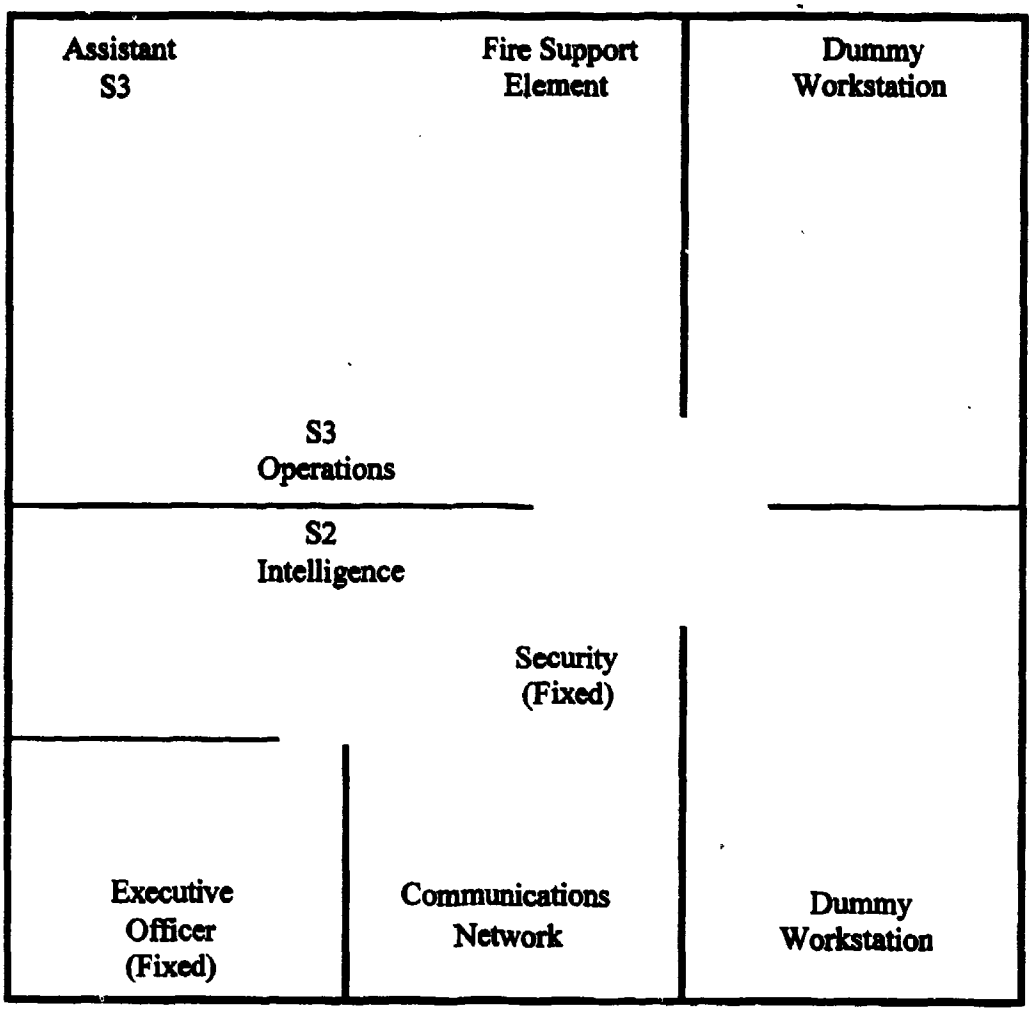

Figure 3. Optimal arrangement of work stations in the notional battalion command post.

COPY CP-9.4 WALLS.4
COPY CP-9.7 STATION.7
COPY CP-9.15 FREQDATA.15

To run the CP-9 model, begin at the system prompt:

Enter **FLAYOUT**

The program will ask

ARE YOU USING AN EXISTING FACILITY STRUCTURE (Y,N)?

Enter **Y**

Then the program will ask

ARE YOU USING AN EXISTING WORKSTATION DATA SET (Y,N)?

Enter **Y**

Then the program will ask

DO YOU WANT TO VIEW THE FACILITY LAYOUT (Y,N)?

Enter either **Y** or **N**

When the system prompt returns

Enter **FOPT**

The program will ask

ARE YOU USING AN EXISTING WEIGHT DATA SET (Y,N)?

Enter **Y**

The program will then ask

DO YOU WANT TO SELECT THE SOLUTION PROCEDURE (Y,N)?

Enter **N**

The program will select Enumeration.

The program will then ask

HOW MANY OF THE TOP SOLUTIONS DO YOU WANT?

Enter any whole number between **1** and **100**.

The results from this model will be in BEST.20. Compare these results with your results generated earlier. Check your ability to **Interpret Results** by comparing the "BEST" arrangement of workstations displayed in the results file (BEST.20) with the workstation arrangement displayed in Figure 3.

This completes the tutorial. You should now be able to develop your own models and run parts of existing models. For specific questions about the programs, see the *Technical Discussion* section beginning on page 35. Once you develop your own model, you should look at the *Analyze Results* section on page 33.

ANALYZE RESULTS

The files useful for analysis are

LAYOUT.8 - Contains the facility structure and the workstation names and locations.

The representation of the layout will seem too wide (north-south direction) because each character space represents a square cell; however, each character is displayed taller than it is wide.

DISTANCE.12 - Contains the distance, in units (10 units = 3 inches) and in inches, between each workstation in the facility.

BEST.20 - Displays in a table format: the solution procedure used; the number of additional starting solutions used and the seed number, if appropriate; the cost and arrangement of the original layout; and the cost and arrangement of the top solutions found. Each column of the arrangement display corresponds to a position. The names displayed in each column are the names of the workstations that occupy each position.

Obtain a hard copy (printout) of the layout matrix (LAYOUT.8).

Note. Most line printers are limited to 133 characters per line. If the facility being modeled is longer than 33 feet in the east-west direction, a hard copy printout of the facility will not contain the entire facility. The unprintable portion, however, can be observed in an editor.

LAYOUT.8 contains the unreduced physical structure and workstation arrangement. The representation of the layout will seem too long in the north-south direction because each character space represents a square cell; however, each character is displayed taller than it is wide.

Draw lines (arcs) on the facility layout hard copy between the workstations and transcribe the distances between the workstations (from DISTANCE.12) onto those lines. Analyze the distance between and relationships among the workstations. Alternate positioning of workstations may become apparent. If so, explore those alternatives.

The results file (BEST.20) displays the original arrangement of workstations (in the order the computer reads the workstations) and the best arrangements found by the solution algorithm. When Enumeration is the selected solution procedure, the worst arrangement is also displayed.

Each column of the original arrangement in the results file corresponds to a position in the original layout matrix. By observing the position of each workstation in the layout matrix and

the column that each workstation is listed in the original arrangement (in the results file), you can determine the position that corresponds to each column.

The workstation name in the first column of the best arrangement is the workstation that should be located in the first position if the best arrangement is accepted.

Write the name of the workstation (in that location-position-column in the best arrangement) on the layout diagram (LAYOUT.8) next to each workstation (original arrangement). Note. You may want to obtain additional hard copies of the layout matrix (LAYOUT.8).

Analyze the best arrangement.

Does this layout make sense?

Are there constraints not modeled that are violated?

Will fixing one or two of the workstations to a location allow a more realistic representation of the facility?

Analyze some of the other top arrangements in this same manner.

How Much Better is the Best Arrangement?

To quantify "How much better is the best arrangement?" we must use the cost value (value of the objective function for each arrangement in the results file, BEST.20).

The goal of the objective function is to minimize the cost of travel within the facility. The cost of travel is the weight of interaction between two workstations multiplied by the distance between those two workstations, summed for all workstation pairs. The weight of interaction between workstations could be frequency of interaction, the product of frequency and priority, a measure of the quality of interaction, or any other measure of interaction between workstations.

[(Original Cost - Best Cost) / Original Cost] * 100 = % Improvement

The percentage improvement is the improvement that the best alternate arrangement can offer over the original arrangement, in terms of the objective function.

Save Results File

To save the results file, you should copy to another file name or rename the results file (BEST.20). The results file will be replaced every time FOPT is executed.

COPY BEST.20 New filename

TECHNICAL DISCUSSION

FLAYOUT

Purpose

The FLAYOUT program is for constructing a model of the physical structure, positioning the workstations, and calculating the distance between each workstation. This program allows a user to construct a model of the physical layout from scratch; use the layout of walls from an earlier model and add workstation locations; construct the layout of the walls and then use an arrangement of workstations from an earlier model; or use a layout of walls and the position of workstations from an earlier model. Reusing modules from other models can save a modeler large amounts of time.

Design Limitations

The FLAYOUT program represents the facility layout as a character matrix. Each character in the matrix represents a 3-inch by 3-inch square cell. The maximum dimensions of the facility to be modeled are 75 feet or 300 3-inch cells per side. To increase the maximum dimensions, a programmer can increase the sizes of the NODE, VAR, STAT, and VIEW matrixes, provided enough memory (RAM) is available.

The maximum area of the facility is 2,000 square feet. This limit is attributable to the method used to calculate the shortest distance between workstations. To increase the maximum area, a programmer can increase the sizes of the N, L, A, D, CL, and P arrays in the SHORT and NET common blocks, provided enough memory (RAM) is available.

The maximum number of workstations contained in the facility is 100. To increase the maximum number of workstations, a programmer can increase the size of the ROOT array and the PLACE matrix in the ROOTNO and NAME common blocks. The programmer will also need to change many variables and some code in the FOPT program.

Exit FLAYOUT

To exit or quit FLAYOUT prematurely, enter "99999" (five nines) in response to any question or prompt.

Input for FLAYOUT

Input files for FLAYOUT are

WALLS.4 - Contains the physical structure of the facility. This file can be an input for FLAYOUT or it can be created in FLAYOUT.

STATION.7 - Contains the names and locations of workstations. This file can be an input for FLAYOUT or it can be created in FLAYOUT.

Creating a New Facility Layout

Make a drawing of the physical structure and locations of workstations for the facility you want to model, add dimensions, and name the workstations before you begin.

The FLAYOUT program will prompt the user, asking for the physical layout and the workstation locations. The FLAYOUT program will always work in a clockwise direction around the perimeter of the facility, starting from the northwest (top left) corner, moving east along the north wall, then south along the east wall, then west along the south wall, and finally north along the west wall, back to the starting location.

Start FLAYOUT, by entering **FLAYOUT** at the system prompt.

Physical Structure

The program will ask

ARE YOU USING AN EXISTING FACILITY STRUCTURE (Y,N)?

Enter **N** (use capital letters to respond to the questions)

Answer the questions the program is asking about the physical structure (exterior and interior walls) of your facility. Follow the question on your diagram. Some questions are asking for a **Y** (yes) or **N** (no) response. For these, be sure your responses are in capital letters. Other questions will be asking for dimensions (numeric responses).

After the dimensions of all the interior walls are entered, the program will create WALLS.4. WALLS.4 contains the facility structure and the program names of every 3-inch-square cell in the facility.

Dimension Responses

The program is looking for two numeric entries: the number of feet and the number of inches. A number must be entered for both numeric entries. However, if your dimensions are all in inches you can enter 0 for feet and the number of inches.

Enter the number of feet, skip a space, and then enter the number of inches.

Example: A wall is 8 feet, 7 inches from the current position.

You can enter

8 7 or **0 103**

All numeric responses must be whole numbers; decimals and fractions are not permitted.

Walls

In this version of FLAYOUT, free standing walls are not permitted. All interior walls must extend from an exterior wall.

Irregular (non-rectangular) Facilities

Non-rectangular arrangement of vehicles or tents can be modeled by positioning interior walls so that certain areas on the periphery of the facility arrangement are not accessible.

For an example, see the command post layout modeled in the *RUN AN EXISTING MODEL* section beginning on page 5. Notice that the enclosed area in the top left cutoff by walls "A" and "H" and the enclosed area in the bottom left cutoff by walls "G" and "F" are inaccessible to human traffic.

Viewing the Physical Layout

To display the layout on the screen, the program reduces the layout matrix. The program reduces the facility (a character matrix) by changing three characters into two characters or changing two characters into one character numerous times, depending on the size of the facility. During this reduction process, extra characters that extend from the corners of the facility are occasionally saved.

If, during the display reduction process, two different characters (at an intersection of two walls, where a workstation is close to a wall, or a workstation has a two-character name) are being reduced to one character, the program will make that one character an @ symbol. Be aware that more than one type of character occupies a space where the @ symbol occurs in the reduced display.

Occasionally, the south wall or the east wall will be displayed as the @ symbol repeated. This occurs sometimes when the layout matrix must be reduced more than once.

Arrangement of Workstations

When the physical structure is complete, the program will ask

ARE YOU USING AN EXISTING WORKSTATION DATA SET (Y,N)?

Enter N

Then the program will ask

DO YOU WANT TO VIEW THE FACILITY LAYOUT (Y,N)?

Enter Y

The program will display a reduced structure, containing the walls you constructed. Each interior wall will be represented by a letter. The outside edge of the facility is represented by "Zs." Make notes on your drawing as to the names of the interior walls.

Answer the questions the program is asking about the location of workstations. The program will be asking you about one workstation at a time. Follow the questions on your diagram.

Again, Y and N responses must be in capital letters and numeric entries have two parts (feet and inches) that must be separated by a space.

Once the data for all the workstations are entered, the program will create STATION.7, the workstation data set, and LAYOUT.8, the facility layout.

Placement of Workstations

Workstations should be placed at least 6 inches, in all directions,

from other workstations or walls. This is to allow room for two-character names and the symbol needed to fix workstations.

After the data for all workstations have been entered, the program will again display the reduced layout matrix. To avoid confusion when this reduced display is viewed, workstations should be placed at least 1 foot, in all directions, from other workstations or walls.

Fixed Workstations

After the location of a workstation is established, the program will ask

IS THIS WORKSTATION TO BE FIXED TO THIS L OCATION (Y,N)?

If you answer Y to this question, the program will put a ^ symbol next to the workstation you are entering. The next program, FOPT, will interpret the ^ symbol to mean the workstation next to it is not to be moved during the optimization.

Correct Workstation Entry Errors

If you notice an error while entering data for a workstation, you can recover. When asked to enter the distance in either direction from the current position enter a distance that is greater than the side dimension of the facility being modeled. The program will tell you an error has been made, erase the workstation you are entering, and then repeat the question before you enter data for the workstation.

If the current position has moved past a location where you wanted to enter the data for a workstation, you can recover. You can enter any workstation in front of a current position, regardless if interior walls are between the current position and the location of the workstation.

Example: If your current position is the corner of the north wall and wall A (the only interior wall connected to the north wall) and you missed entering the Assistant S3 before wall A,

You can continue and enter the rest of the workstations in front of the North wall after wall A.

Then, when your current position has moved to the corner of the north wall and the east wall, you can enter the workstation you missed before wall A. Be careful

to calculate the proper distances from the current position to the workstation. The distance in the north-south direction will be approximately 2 feet and in the east-west direction approximately 12 feet (10 feet to wall A + 2 feet past wall A).

Note. The workstation entered out of sequence will have a program-assigned name--also out of sequence.

Other workstation entry errors (moving workstation locations and fixing or freeing workstations) must be corrected after FLAYOUT has completed. You can either execute FLAYOUT again and enter the workstations again or follow the instructions in the Correct the Workstation Data Set section beginning on page 40.

Viewing the Facility Layout

After the workstation data are entered, the program will then ask

DO YOU WANT TO VIEW THE FACILITY LAYOUT (Y,N)?

Enter Y

The program display is a reduced layout, including the structure of the walls and the locations and names of the workstations. Each workstation will be represented by a program-assigned name (a number, a letter, or a letter and a number). Make notes on your drawing as to the program names of the workstations.

Also displayed will be the "NUMBER OF ARCS" and the "NUMBER OF WORKSTATIONS." The number of arcs is the shortest path arcs generated for the shortest path algorithm. This number will be larger for larger area facilities. The number of workstations is self-explanatory. The time required by the shortest path algorithm to reach a solution is a function of the "number of arcs" and the "number of workstations."

Correct the Workstation Data Set

If you observed an error when you entered the workstations, you do not have to re-enter all the workstations to correct the mistake.

1) Obtain a hard copy of LAYOUT.8.

LAYOUT.8 contains the unreduced physical structure and workstation arrangement. The representation of the layout will seem too wide (north-south

direction) because each character space represents a square cell; however, each character is displayed taller than it is wide.

2) Analyze the Facility Layout.

Analyze the position of workstations in the layout (LAYOUT.8). Select the modifications needed to correctly model the workstation arrangement. Make estimates for the distances workstations need to be moved or the distances from the top and left side to locations where workstations are to be added.

Note. The workstation data set is in STATION.7. You are analyzing and gathering measurements from the facility layout (LAYOUT.8) to enable you to modify the workstation data set (STATION.7), because the workstation data set contains only the workstations and no points of reference, such as interior walls.

3) Change the workstation data set.

Move a Workstation

a) Enter STATION.7 into a text editor.

b) Move your cursor to the workstation.

c) Move the cursor the appropriate spaces (one space represents 3 inches) from the old location to the new location of the workstation.

d) Enter the workstation name (number or letter).

e) Return the cursor to the original position of the workstation, and erase the workstation from the original location.

Add a Workstation

a) Enter STATION.7 into a text editor. The top line of STATION.7 displays the dimension of the facility in units (10 units = 3 inches = 1 character space = 1 vertical line).

b) Realizing the top line is not part of the facility and that the north wall occupies 3 inches (another line), move the cursor down the appropriate number of lines to the horizontal location of the new workstation.

c) Realizing the first character is always blank to avoid confusion with certain line printers and that the west wall occupies 3 inches (accounting for two spaces), move the cursor horizontally to the location of the workstation to be added.

d) Add the name (number or letter) of the new workstation. The name of the new workstation cannot be the same as one of the other workstations.

Workstation Names

Workstation names or program names can be one or two characters. One character names can be any digit or capitalized alphabetic character. Two character names must have the first character a capitalized alphabetic character and the second a digit. Workstation names cannot be used more than once.

Fix or Free a Workstation

a) Enter STATION.7 into a text editor.

b) Move the cursor to the workstation.

c) To fix the workstation, add the ^ symbol (shift 6) next to the workstation; directly in front of the workstation is the preferred position. However, if the workstation is next to a wall or close to other workstations, other positions for the ^ symbol must be found. The ^ symbol can be placed above or below the first character in the workstation name or in the second space behind the first character of the workstation name. Analyze the facility layout (LAYOUT.8) to determine if positions other than in front of the workstation must be used for placement of the ^ symbol.

d) To free a workstation, simply erase the ^ symbol that is next to the workstation.

4) Run FLAYOUT after changing the locations of workstations (in STATION.7). This will produce the correct data input files for the next program (FOPT).

If the only changes you made in STATION.7 were to fix or free workstations, you do not need to re-run FLAYOUT.

Save a Facility Layout

To save the facility layout you just created, you should copy to another

file name or rename the input files. The input files are

WALLS.4

STATION.7

If these input files are not renamed, they will be replaced when new models are created.

Running an Existing Facility Layout

The needed input files to run FLAYOUT are

WALLS.4 - Contains the physical structure of the facility.

STATION.7 - Contains the workstation names and locations.

Select the model you wish to run and copy the appropriate files to WALLS.4 and STATION.7.

If you want to use a physical structure and re-position the workstations, only WALLS.4 is needed.

If the workstations need only minor adjustments, a text editor can be used to modify an existing workstation data set (STATION.7) outside FLAYOUT. See section entitled *Correct the Workstation Data Set*, page 23.

If you like the location of the workstations but want to change the physical structure slightly, only STATION.7 is needed. However, if you construct a facility of a size different from the one used when STATION.7 was created, the program will crash.

Start FLAYOUT at the system prompt.

Enter **FLAYOUT**

The program will ask

ARE YOU USING AN EXISTING FACILITY STRUCTURE (Y,N)?

Enter **Y**

If WALLS.4 contains the facility structure you want to model.

The program will ask

ARE YOU USING AN EXISTING WORKSTATION DATA SET (Y,N)?

Enter Y

If STATION.7 contains the workstation data set you want to model.

Output from FLAYOUT

WALLS.4 - Contains the physical structure of the facility. This file is written only if a facility structure was created.

STATION.7 - Contains the workstation names and locations. This file is written only if workstations were created. This file is an input file for FOPT.

LAYOUT.8 - Contains the physical structure and the workstation names and locations. This file is useful for analyses. The facility will seem longer in the north-south direction because each character represents a square, but when displayed, characters are taller than they are wide.

DISTANCE.12 - Contains the distance between each workstation in an easy-to-read format. This file is an input file for FOPT. Distances are displayed in units and in inches. Units are used for calculations in FOPT. The value of a unit is defined by the following relationship: 10 units = 3 inches.

NUMSTAT.13 - Contains the number of workstations. This file is an input file for FOPT.

FOPT

Purpose

The FOPT program is used to generate and evaluate alternate facility arrangements of workstations. This program uses the distance between workstations and the weights of interaction between workstation pairs to evaluate facility arrangements. The goal of the optimization procedures (used to generate alternate arrangements) is to find the least cost arrangement of workstations. The cost of an arrangement is the sum of the products of distance and weight for every interaction between workstations. Eight different optimization procedures are available.

Distance Matrix

FOPT reads DISTANCE.12 generated by FLAYOUT and creates a distance matrix. Entries in the distance matrix represent the distance between all pairs of workstations in units (10 units = 3 inches). In FOPT, the distance matrix is the DIST matrix. Each workstation occupies a row and a column of the DIST matrix, making the matrix symmetrical about the diagonal. The columns and rows of the distance matrix are in the same order as that used by the computer to read the workstation data in FLAYOUT.

Weight Matrix

The weight matrix (FREQDATA.15) contains the weight of interaction between all pairs of workstations. In FOPT, the weight matrix is in the FREQ matrix. A weight of interaction can be the frequency of interaction; a measure of the quality of interaction; a combination of frequency and priority; a combination of frequency and the ability to communicate with other workstations; or any other method of measuring interaction.

The weight of interaction between Workstations 1 and 2 is the same as the weight of interaction between Workstations 2 and 1. Most data-collection techniques distinguish between, from Workstations 1 to 2 and from Workstations 2 to 1. If your weight of interaction data are in this form, add the entries together. For example, if the weight from Workstations 1 to 2 is 10 and the weight from Workstations 2 to 1 is 4, make the weight of interaction between Workstations 1 and 2 equal to 14. The 1, 2 cell and the 2, 1 cell in the weight matrix will have the entry 14.

The weight matrix can be created in FOPT or imported from a source outside FOPT. Once a weight matrix has been used by FOPT, the columns and rows are labeled with the workstation name (the name generated in FLAYOUT). This allows an analyst to modify the locations of the workstations in STATION.7, keeping the same workstation names; rerun FLAYOUT; and use the same weight matrix when executing FOPT.

A weight matrix from an external source (SAS data set, D-base file, text editor, etc.) must also be symmetric about the diagonal. That is, the weight from 1 to 2 must be the same as the weight from 2 to 1. The external weight matrix being used for the first time by FOPT must have one blank line at the top of the file. This blank line will be replaced by the names of the columns during execution of FOPT.

The weight matrix from an external source should be in the following format:

100(I3,1X)	A right-justified three-digit whole number, one space, and then another right-justified three-digit whole number, one space, and so on. The number of columns (three-digit numbers) of the matrix must correspond to the number of workstations. Currently, this format can read a maximum of 100 workstations.

A programmer can change the "888 FORMAT" statement in the main program driver of FOPT and re-compile FOPT if this format is not acceptable. However, if you do change this format statement, all your existing weight matrices must also be changed.

Design Limitations

The FOPT program limits the number of workstations to 100. To increase this maximum number, a programmer will need to increase the array and matrix sizes of the variables in the DATA, WHERE, GOOUT, and NODES common blocks and increase the array sizes of TOCK in the main program driver; TBEST in the SORT subroutine; T in the PRINT subroutine; P, LIST, T, TLOC in the VNZ, terminal sampling procedure (TSP), and modified TSP (MTSP) subroutines; and T and TLOC in the PAIRS, WAY23, WAY32, and STEEP subroutines. The programmer will also need to change the first IF statement in the main program driver. The programmer will also need to change the "888 FORMAT" statement in the main program driver.

Exit FOPT

To exit or quit FOPT prematurely, enter "99999" (five nines) in response to any

question or prompt except the question asking for a seed number for the random solution generator (you cannot abort directly from this question).

Input for FOPT

Input files for FOPT are

STATION.7 - This file is created in FLAYOUT and it contains the workstation names and locations. It is also used to check if a workstation is fixed to its location. Note. If the location of a workstation is changed outside FLAYOUT, FLAYOUT must be rerun before executing FOPT. However, if STATION.7 is only changed outside FLAYOUT by fixing or unfixing workstations, FLAYOUT does not need to be rerun.

DISTANCE.12 - Contains the distance between workstations. This file is created in FLAYOUT. It is used to create the distance matrix.

NUMSTAT.13 - Contains the number of workstations. This file is created in FLAYOUT.

FREQDATA.15 - Contains the weight of the interaction between workstations. This file can be created in FOPT or outside FOPT.

Optimization Algorithms

The problem of assigning n workstations to n locations for the purpose of minimizing the sum of inter-workstation interaction costs is a quadratic assignment (QA) problem. The mathematical structure of the QA problem does not lend itself to solution, except by enumeration or implicit enumeration (branch-n-bound) algorithms. Enumeration and implicit enumeration algorithms are not efficient search procedures, limiting the size of problems that can be solved. One exact solution procedure (a procedure that will always find the optimal solution) and seven heuristic procedures (decision rules that improve but do not guarantee the optimal solution) are available in FOPT.

Enumeration

Enumeration is the only exact (will guarantee optimal) solution procedure available in FOPT. It generates and evaluates every possible arrangement of workstations. Because of the exhaustive search of all arrangements, this procedure can only be used for problems with fewer than 12 free-to-move (not fixed) workstations. However, solving problems with 10 free-to-move (not fixed) workstations will require approximately 1 hour of computer time. To solve an 11-workstation problem will require slightly more than 11 times as much

computer time as required for the 10-workstation problem. The largest problem the Enumeration algorithm in FOPT will solve is a 12-workstation problem, regardless of the number of fixed workstations.

Heuristics

Seven heuristic procedures are available. Heuristic procedures will find good quality (low cost) solutions; however, finding the optimal solution is not guaranteed.

Some heuristics normally produce better quality (lower cost) solutions than others do. However, for test problems, each heuristic found a better solution than the other heuristics did for certain problems. The following heuristic solution procedures are listed in the order of average solution quality that each heuristic will produce, with the first producing the lowest average cost of solutions:

1) Steepest 3-way interchanges and then 2-way interchanges.

2) Computerized relative allocation of facilities technique (CRAFT) steepest 3-way or 2-way interchanges.

3) CRAFT steepest 2-way interchanges and then a steepest 3-way interchange.

4) Terminal-sampling procedure (Hitchings & Cottam, 1976).

5) A modified terminal sampling procedure.

6) CRAFT steepest 2-way interchanges (Armour & Buffa, 1963).

7) Computerized office layout (COL) (Vollmann, Nugent, & Zartler, 1968).

A rank ordering, by the time required to reach a solution, for the heuristics would be approximately reverse order of the rank ordering above, with COL (the last) being the quickest.

If you allow the program to select the solution procedure, it will select a procedure based on the number of workstations in the problem. The following is the list of solution algorithms that the program will select:

Number of Workstations	Algorithm
9 or fewer	Enumeration
10 to 15	Steepest 3-way interchanges and then 2-way interchanges
16 to 25	CRAFT steepest 2-way interchanges and then a steepest 3-way interchange
26 or more	COL procedure.

This general selection rule is based on average solution quality and speed. More information about this is presented in Appendix A of this report.

Starting Arrangements

For a heuristic procedure to find better solutions (closer to optimal) to problems, the authors of the various heuristic procedures suggest using as many different starting solutions (starting arrangements) as possible. Each heuristic procedure makes step-wise improvements (changes) in the current arrangement. Different starting arrangements will allow different sets of step-wise improvements to be made, possibly reaching different and better final solutions (arrangements).

Recommendation

Each heuristic procedure can find a solution superior to the solution found by the other heuristic procedures, depending on the starting solution (initial arrangement). Each heuristic procedure makes a different set of changes to improve a solution. Thus, to find the best solution for large problems, you should use (run) as many different heuristic solution algorithms and starting solutions as time allows.

For more information about the expected solution quality, speed of solution, or the actual workings of each algorithm, the interested reader is directed to Appendices A and B of this report.

The analyst interested in research to find the best solution to large problems will find suggested approaches presented in Hitchings and Cottam (1976).

ANSWER.9 should be useful to the analyst for finding the best solution to large problems. ANSWER.9 contains all the starting solutions and final solutions generated and solved during a FOPT run.

FOPT Execution

Start FOPT at the system prompt.

Enter **FOPT**

The program will

Read NUMSTAT.13,

Read DISTANCE.12 and create the distance matrix,

Read STATION.7 and check for fixed workstations,

And then ask

ARE YOU USING AN EXISTING WEIGHT DATA SET (Y,N)?

Manually Enter the Weight Matrix

Enter **N**

The program will display the current order of the workstations (order produced by FLAYOUT) and prompt you for information about the interaction between each pair of workstations.

A numeric response is expected for every pair of workstations. If no interaction is possible between two workstations, enter zero (0).

Use a Weight Matrix That Already Exists

Enter **Y** FREQDATA.15 must contain the weight matrix you want to use.

If the weight data set has not been used before by FOPT, read the ***Weight Matrix*** section, starting on page 45, before proceeding.

1) If you entered **Y** and FREQDATA.15 has a **blank line at the top**, the program will display the current order of workstations and ask

IS THIS THE CORRECT ORDER (Y,N)?

a) If you enter **Y**, the current order will be written at the top of FREQDATA.15, as a header for future runs.

b) If you enter **N**, the program will ask you the name of each column of the weight matrix. Use the names given to the workstations in FLAYOUT.

If you make an error in entering the workstation names, the program will tell you and ask if you want to re-enter the workstation name, re-enter all the workstation names, or quit the program.

2) If you entered **Y** and FREQDATA.15 has **workstations names in the top line**, the program will compare those names with the names generated in FLAYOUT.

a) If the names are the same, the program will accept the order of the weight matrix and continue through the rest of the program.

b) If the names are different, the program will acknowledge that an error has been made but will not abort. Instead, it will proceed as if the top line in FREQDATA.15 were blank.

3) If you enter **Y** and FREQDATA.15 does not have a blank line or a header with workstation names at the top of the file, the program will crash, and a list of system error messages will be displayed on your terminal screen.

You should add a blank line to the top of FREQDATA.15 and re-execute FOPT.

Select the Solution Procedure

After the weight matrix has been read and its order established, the program will ask

DO YOU WANT TO SELECT THE SOLUTION PROCEDURE (Y,N)?

For the program to select an optimization algorithm (solution procedure)

Enter **N** The program will make the selection based on the size of the problem being modeled (see page 49).

For you to select an optimization algorithm (solution procedure),

Enter **Y**

The program will instruct you to select a solution algorithm and display the names of the available optimization algorithms. For small problems of nine or fewer workstations, enumeration should be used.

Enumeration is the only exact solution procedure available. That is, enumeration will always find the optimal answer. However, enumeration is very time consuming for large problems, making problems with more than 10 free-to-move (not fixed) workstations unreasonable to solve. In the FOPT program, enumeration will not solve a problem with more than 12 workstations.

The other solution procedures are **heuristic** procedures. The heuristics are improvement procedures that will make step-wise improvements (modifications) in a starting arrangement (starting solution), until no further improvements are possible. The heuristic procedures will not always find the optimal solution but will find improved (possibly optimal) solutions. The quality of the solution found by a heuristic depends on the starting arrangement.

If a heuristic procedure is selected the program will execute the procedure, finding the best solution that can be found using the procedure and the starting arrangement of workstations.

Then the program will ask

HOW MANY ADDITIONAL STARTING ARRANGEMENTS SHOULD BE RUN?

When this question is asked, the program has solved the original problem with the selected heuristic. The program is now offering to generate additional starting arrangements and solve them with the selected heuristic.

Enter a number between **0** and **100**

Programmer's Note. To increase the maximum number (100) of additional starting arrangements to be run, a programmer will need to modify the PICKNO subroutine.

If you enter a number greater than zero (0), the program will ask

ENTER A SEED NUMBER FOR THE RANDOM SOLUTION GENERATOR

Enter any whole number - the random solution generator works best when an odd number with five or more digits is entered.

Note. If finding the optimal solution to large problems is important, you should use as many different heuristic solution procedures and as many different starting solutions as possible.

If enumeration or a heuristic is selected, the program will ask

HOW MANY OF THE TOP SOLUTIONS DO YOU WANT?

Enter any number between **1** and **100**.

When enumeration is the optimization algorithm, the program will display in table format as many of the top solutions as requested.

When a heuristic is used, the program may display fewer top solutions than were requested. Only five of the top solutions are saved from the solution of each starting arrangement. If more than one starting arrangement is run, then more than five top arrangements can be displayed. However, the program is only going to save unique arrangements.

The program will then solve the problem, save as many of the top solutions as requested, and print a summary report (BEST.20).

Save the Weight Data Set

To save the weight data set (FREQDATA.15) that you created or that was modified by FOPT, you should rename it or copy it to another file name. This input file, if not renamed, will be replaced when a new weight data set is created or imported from other sources.

Output From FOPT

FREQDATA.15 - This file is the weight matrix and it is written by the program only if it was created or modified (file header created) during the run.

ANSWER.9 - This file is only written when a heuristic solution procedure is used. It contains the starting arrangements and the top solutions found for each starting arrangement. This file is useful for in-depth analyses to find the optimal solution for large problems.

BEST.20 - This file is a summary report of the results. It displays the solution procedure used; the number of additional starting solutions used and the seed number, if appropriate; the original cost and arrangement; and the cost and arrangement of the top solutions found. If enumeration was the solution procedure used, this report will also display the worst solution's cost and arrangement.

The position of workstations in the facility layout corresponds to the column that the workstation program name is displayed in the original arrangement. Each column of all the arrangements displayed corresponds to a position in the facility layout. The names displayed in each column are the names of the workstations that occupy each position in the various arrangements.

In the original arrangement, an "F" will be displayed behind a workstation that is fixed to its location. In each arrangement generated by the program, a fixed workstation should be displayed in the same column.

Interpret Results

Obtain a hard copy of **BEST.20**.

By observing the location of each workstation in LAYOUT.8 and the column in which each workstation is listed in the original arrangement (found in BEST.20), you can determine the position that corresponds to each column. The position of workstations in the facility layout corresponds to the column that the workstation program name is displayed in the original arrangement. Each column of all the displayed arrangements corresponds to a position in the facility layout.

In the original arrangement, an "F" will be displayed behind a workstation that is fixed to its location. In each arrangement generated by the program, a fixed workstation should be displayed in the same column.

The names displayed in each column are the names of the workstations that occupy each position in the various arrangements. If workstation 2 is in the first column of the best arrangement and you had constructed the facility with workstation 1 in the first position (column) of the original arrangement, you should write workstation 2 into the position that workstation 1 occupied in the original arrangement. Write the workstation names from the best arrangement in BEST.20 into the appropriate positions in the facility layout (LAYOUT.8).

See the *Analyze Results* section, page 33, for more detail about how to use the results produced by FOPT.

ERROR MESSAGES

FLAYOUT

The following are explanations of possible error messages encountered when using the FLAYOUT program.

EXPECTED ENTRY NOT MADE *** ERROR ***
CHECK THAT ENTRY IS IN CAPITAL LETTERS
RE-ENTER RESPONSE OR 99999 TO QUIT

This error occurs when the program is expecting a Y or N response to a Yes or No question. Be sure your responses are made in capital letters.

THE WORKSTATION DATA SET IS NOT THE SAME SIZE AS THE FACILITY STRUCTURE.
*** ERROR *** ENTER WORKSTATIONS OR ABORT PROGRAM

The size of the workstation data set (STATION.7) you are trying to use is different from the size of the facility structure (WALLS.4). Your only options are to construct a new workstation data set or abort the program, copy another file to STATION.7, and rerun FLAYOUT. The program will ask if you want to abort the program.

XX IS NOT A LEGAL WORKSTATION NAME
*** ERROR *** ENTER WORKSTATIONS OR ABORT PROGRAM

Workstation *XX* in STATION.7 does not have a legal name. Other workstations in STATION.7 may also not have legal names. *XX* was just the first illegal name found. Your only options are to construct a workstation data set or abort the program, copy another file to STATION.7, and rerun FLAYOUT. The program will ask if you want to abort the program.

ENTRY IS NOT IN CORRECT FORMAT
ENTRY SHOULD BE NUMERIC, NO. FEET THEN ONE SPACE AND NO. INCHES.
*** ERROR *** RE-ENTER RESPONSE OR 99999 TO QUIT

You entered numeric data in a format that was not acceptable. Sometimes this error message will include additional information to help you avoid making the same mistake. Re-enter your response.

NUMBER OF FEET IS TOO LARGE
ENTRY SHOULD BE NUMERIC, NO. FEET THEN ONE SPACE AND NO. INCHES.
*** ERROR *** RE-ENTER RESPONSE OR 99999 TO QUIT

The program is checking if the entered data are in the proper format. Your entry was not acceptable. If you are entering dimensions in inches, enter zero (0) for feet, skip one space, and enter the number of inches. Sometimes an error message will state that the "NUMBER OF INCHES IS TOO LARGE." The number of feet and the number of inches cannot be larger than the facility being modeled.

*** ERROR *** IN FORMAT. NO INCHES WERE ENTERED.
ENTER THE NUMBER OF INCHES.

The program was excepting your numeric entry to be the number of feet, one space, and the number of inches. It only read the number of feet and now wants you to enter the number of inches.

LENGTH IS GREATER THAN 75 FEET.
*** ERROR *** RE-ENTER LENGTH

The facility is limited to a maximum of 75 feet per side. The length is the east-west direction.

WIDTH IS GREATER THAN 75 FEET.
*** ERROR *** RE-ENTER WIDTH

The facility is limited to a maximum of 75 feet per side. The width is the north-south direction.

THE AREA OF THE FACILITY EXCEEDS 2,000 SQUARE FEET.
*** ERROR *** RE-ENTER BOTH LENGTH AND WIDTH.

Total area of the facility, length * width, cannot exceed 2,000 square feet. If the facility you are modeling is larger, can you reduce the dimensions? As a last resort, FLAYOUT can be modified, see *Design Limitations* in the FLAYOUT section, page 39, for a brief overview of the procedure.

*** ERROR *** DISTANCE TO WALL IS TOO LARGE.
START ENTERING WALLS THAT EXTEND FROM THE XXX WALL AGAIN.

The distance to the next wall exceeds the boundary (either length or width) of the facility. All walls previously entered along the XXX exterior wall have been erased. Start entering interior walls along the XXX exterior wall again.

*** ERROR *** WALL LENGTH IS TOO LARGE.

The length of the interior wall being currently entered is too long. Re-enter the length of this wall. All walls previously entered are unaffected.

DISTANCE FROM CURRENT POSITION MUST BE AT LEAST 3 INCHES.
*** ERROR *** RE-ENTER X DISTANCE.

Workstations must be at least 3 inches in the X and the Y directions away from all the walls. One foot away from the walls is suggested to make the analysis and model development easier. Note: The program asks for the X direction before asking for the Y direction. Sometimes an error message that states RE-ENTER BOTH X AND Y DISTANCES, may occur. The Y distance entered was too small. You must re-enter both the X and Y distances.

LOCATION IS OUTSIDE THE FACILITY.
*** ERROR *** RE-ENTER WORKSTATION.

The dimension entered in either the X or Y direction exceeded the size of the facility. The workstation must be re-entered.

ANOTHER WORKSTATION IS AT THIS LOCATION.
*** ERROR *** RE-ENTER WORKSTATION.

Workstations must be at least 6 inches apart in all directions. The workstation must be re-entered.

WORKSTATIONS CANNOT BE INSIDE OF A WALL.
*** ERROR *** RE-ENTER WORKSTATION.

A wall exists at the location of this workstation. Re-enter the workstation.

SPACE IS TOO SMALL FOR A WORKSTATION.
*** ERROR *** RE-ENTER WORKSTATION.

A workstation may require 9 inches of space, 6 inches for the two-character name and 3 inches for the symbol to fix the workstation. This error message occurs when (1) other workstations or (2) the walls are too close to the workstation being entered. The workstation must be re-entered.

FOPT

The following are explanations of possible error messages encountered when using the FOPT program.

EXPECTED ENTRY NOT MADE *** ERROR ***
CHECK THAT ENTRY IS IN CAPITAL LETTERS
RE-ENTER RESPONSE OR 99999 TO QUIT.

This error message normally occurs when the program is expecting a Y or N response to a Yes or No question. Be sure your responses are being made in capital letters.

RESULTS FROM FLAYOUT DO NOT MATCH WITH STATION.7.
*** ERROR *** ABORT PROGRAM

The workstation data set (STATION.7) has been modified or replaced since FLAYOUT was last run. Run FLAYOUT before attempting to run FOPT again.

THE WORKSTATION NAMES DO NOT MATCH.
*** ERROR *** BUT NOT FATAL, CONTINUING.

The header on the weight matrix (FREQDATA.15) has workstation names different from those generated in FLAYOUT or an error in entering the names has been made. Additional information describing the error may also be displayed. The program will ask if you want to abort the program or select another option. If you do not abort the program, you must enter the order of the columns of the weight matrix. The program will then rewrite the header on FREQDATA.15.

ENTRY IS NOT IN CORRECT FORMAT
*** ERROR *** RE-ENTER RESPONSE OR 99999 TO QUIT

You made a numeric entry in the wrong format. Re-enter your response. This error message will contain additional information, useful for helping you to avoid making the same mistake. Enter "99999" to abort or stop the program.

ENUMERATION IS NOT AVAILABLE FOR PROBLEMS WITH MORE THE 12 WORKSTATIONS.
*** ERROR *** SELECT ANOTHER SOLUTION PROCEDURE.

Your facility has more than 12 workstations. One of the heuristics solution procedures is required.

THE NUMBER OF TOP SOLUTIONS REQUESTED CANNOT BE ZERO.
*** ERROR ***

The program must supply you with at least one solution. Re-enter your request.

System Errors

Occasionally, a system error (outside the program) will occur. This will normally be caused by the program's attempt to read past the end of a file. If this is the case, verify that the file exists. If the file is FREQDATA.15, check that a header (one line, either blank or with workstation names) is at the top of the file. Other system errors may be a result of insufficient memory being defined. Four megabytes of memory are needed to run FLAYOUT and FOPT. Consult your system's FORTRAN manuals for complete understanding of system errors.

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APPENDIX A

MATHEMATICAL DESCRIPTION OF THE QUADRATIC ASSIGNMENT PROBLEM

MATHEMATICAL DESCRIPTION OF THE QUADRATIC ASSIGNMENT PROBLEM

Subscripts

i & j are workstations or personnel.

h & k are sites or locations.

n = the number of workstations and sites.
No. workstations = No. sites = n.

Variables

d_{hk} = Matrix of distances between sites h and k.

w_{ij} = Matrix of weights of interactions between workstations i and j.

x_{ik} = Decision variable equal to one if workstation i is located at site k. Otherwise, it is equal to zero.

x_{jh} = Decision variable equal to one if workstation j is located at site h. Otherwise, it is equal to zero.

Objective function

$$\text{Minimize } f(x) = \sum_{i=1}^{n-1} \sum_{k=i}^{n} \sum_{j>i}^{n} \sum_{h=j}^{n} w_{ij}\, d_{hk}\, x_{ik}\, x_{jh}$$

Minimize the distance of highly weighted interactions.

Subject to

$$\sum_{i=1}^{n} x_{ik} = 1 \quad k=1,\ldots n$$

Ensures that only one workstation is assigned to each site.

$$\sum_{k=1}^{n} x_{ik} = 1 \quad i=1,\ldots n$$

Ensures that each workstation is assigned to only one site.

APPENDIX B

SOLUTION OF THE QUADRATIC ASSIGNMENT PROBLEM

SOLUTION OF THE QUADRATIC ASSIGNMENT PROBLEM

Facility arrangements that maximize the quality of interaction can increase efficient performance of the organization's goals. The problem of achieving this efficiency by optimally arranging departments, personnel, equipment, or work..tations falls into a class of problems known as the quadratic assignment (QA) problem. Solution procedures for QA problems seek to maximize the quality of interaction by minimizing the cost of interaction (material handling and personnel movement costs) between elements (hereafter referred to as workstations) in the facility. The cost per distance of interaction between workstations can be extended to many types of interaction; for example, paper flow in an office can represent a cost; people must walk to and from other individuals or equipment, the transit time can represent a cost; the priority of a communication can increase the cost of transit time between individuals or individuals and equipment.

The QA problem is to assign n workstations into n locations (sites) to minimize the sum of inter-workstation interaction costs. A mathematical description of the QA problem is presented in Appendix B. A variety of procedures has been developed to find least cost solutions, some of which are exact and many of which are approximate (heuristic procedures). Exact solution procedures find the optimal assignment of workstations to locations, but even the most efficient algorithms (branch and bound algorithms) are computationally infeasible to use when the number of workstations is greater than 15 (Burkard, 1984; Francis & White, 1974, pp. 336; Reeves, 1985; and Tompkins & White, 1984)[1]. Heuristic procedures do not guarantee that an optimal, least cost assignment will be found, but they can be used to generate good solutions for large real-world problems.

The heuristic approaches presented in FLOT are deterministic; that is, given a starting solution, the algorithm proceeds via a particular route, without deviation, to a particular improved final solution. Hence, the final solution generated by a particular algorithm for any given starting arrangement will always be the same. Authors of these deterministic approaches suggest a variety of starting solutions be used.

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[1]A computationally complex procedure for optimally solving QA problems with as many as 25 workstations has been developed by Christofides and Benavent (1989). Their technique requires a dynamic programming algorithm to solve a Lagrangian relaxed formulation of the QA problem to obtain a lower boundary of the optimum. Then a branch and bound reduction method based on the lower boundary is used to decrease the number of variables for an integer programming optimization.

Algorithms

The algorithms available in the current version (2.0) of FLOT (in order of the subsequent discussion) are

- Enumeration
- CRAFT-2, pair-wise exchanges (Armour & Buffa, 1963)
- COL (Vollmann, Nugent, & Zartler, 1968)
- TSP (Hitching & Cottam, 1976)
- Modified TSP
- CRAFT2-3, 2-way exchanges before a 3-way exchange
- Steep3-2, best 3-way exchanges before any pair-wise exchanges
- CRAFT-32, best 3- or 2-way exchanges

Enumeration

Enumeration generates all possible arrangements (n!) of workstations at locations, calculates the cost of an arrangement, and compares the cost with the cost of other arrangements to find the least cost arrangement (assignment). The cost of an arrangement is the sum of the products of distance and weight for every interaction between workstations. This algorithm can be used for problems with 12 ($n = 12$) or fewer workstations. However, problems with more than 10 free-to-move workstations ($n > 10$) may not be computationally feasible to solve using Enumeration. The computations required are not complex; however, n factorial iterations require an immense amount of computation time. Enumeration is the only exact solution procedure in the FLOT.

CRAFT-2

CRAFT, which was developed by Armour and Buffa (1963), is the most commonly used heuristic procedure. The algorithm searches for improvements (assignments with a lower total cost) to an initial (starting) solution. To find improvements, the algorithm explores all 2-way interchanges of workstation locations and calculates the potential cost reduction of each. Then the algorithm makes the interchange of workstation locations that provides the greatest reduction in total cost. The procedure is repeated until no further reduction in total cost is available. In each iteration there are $n(n-1)/2$ pairwise cost reduction calculations performed.

COL

The COL procedure was developed by Vollmann, Nugent, and Zartler (1968) to produce good quality solutions, using less storage space and computation time than CRAFT. The algorithm uses a two-phase procedure to improve an initial solution. Phase I starts by identifying the highest and second highest cost workstations. Then, for each remaining workstation, it is determined if there would be a reduction in total cost if its location were interchanged with the location of the highest cost workstation. Those workstations whose interchanges would produce a cost reduction are then listed from greatest to least according to magnitude of the potential cost reduction. The location of the workstation at the top of the list is then interchanged with the location of the highest cost workstation. The next workstation in the list is then considered. If the interchange of its location with the current location of the highest cost workstation would produce a cost reduction, the interchange is made; if not, the interchange is not made. Going down the list, each workstation is considered in the same manner and its location interchanged with the current location of the highest cost workstation, if a cost reduction can be achieved.

When the list is exhausted, a new list is generated in the same manner as the earlier list except that the second highest cost workstation is used for cost reduction comparisons rather than the highest cost workstation. The location of the workstation at the top of the new list is then interchanged with the location of the second highest cost workstation. Subsequently, the location of each of the remaining workstations on the list is interchanged with the current location of the second highest cost workstation, if such an interchange would produce a cost reduction. When this list is exhausted, a redetermination of the highest and second highest cost workstations is made (depending on the data, the highest cost workstations change). The entire process is repeated until two highest cost workstations are found that neither can be interchanged with any workstation to reduce total cost. This is the end of Phase I.

In Phase II, any pair-wise interchange of workstation locations that will reduce total cost is made. Pair-wise interchanges are repeated until no further reduction in total cost is available. No attempt, in Phase II, is made to make the interchange that produces the greatest reduction in cost (contrary to CRAFT pair-wise exchanges). Currently, this algorithm is the fastest algorithm that produces good quality solutions.

TSP

By combining CRAFT and COL, Hitchings and Cottam (1976) developed TSP. This improved algorithm modifies Phase I of the COL by performing one CRAFT pair-wise loop after each highest or second highest cost workstation has completed interchanges with workstations on its list (based on phase I, COL). Then Phase II of COL is replaced by CRAFT pair-wise loops, until no further improvement is available. Adding the CRAFT loops to COL increased slightly the number of computations.

Modified TSP

The MTSP algorithm preforms a CRAFT pair-wise loop at the end of each COL phase I iteration. Each COL Phase I iteration is completed when interchanges of workstations on the highest cost workstation's list and the second highest cost workstation's list are done.

CRAFT2-3

The CRAFT2-3 algorithm explores all 2-way interchanges of workstation locations and makes the interchange that provides the greatest reduction in total cost. This process is repeated until no further reduction in total cost is available from 2-way interchanges (same as CRAFT-2). Then all 3-way interchanges of workstation locations are explored and the interchange that provides the greatest reduction in total cost is made. After one 3-way interchange loop, the algorithm returns to 2-way interchanges, repeating the entire process until no further reduction in total cost is available. The computation time required by this algorithm is slightly more than CRAFT pair-wise exchanges and significantly less than other 3-way exchange procedures, as most of the iterations require $n(n-1)/2$ cost-reduction calculations.

Steep3-2

The Steep3-2 algorithm explores all 3-way interchanges of workstation locations and makes the interchange that provides the greatest reduction in total cost. This is repeated until no further reduction in total cost is available from making 3-way interchanges. Then any pair-wise interchanges that reduce total cost are made, until no further reduction in total cost is available. No attempt to make the pair-wise interchange that produces the greatest reduction in cost is made (in the same manner as COL Phase II). After the pair-wise interchanges, the entire process is repeated until no further reduction in total cost is available. Each iteration of 3-way interchanges requires $n(n-1)(n-2)/3$ cost-reduction calculations. This increases computation time considerably for larger problems.

CRAFT-32

The CRAFT-32 algorithm explores all 3- and 2-way interchanges of workstation locations and makes the interchange that provides the greatest reduction in total cost. This process is repeated until no further reduction in total cost is available. Each iteration requires $n(n-1)(n-2)/3 + n(n-1)/2$ cost reduction calculations, which increases computation time considerably for larger problems.

Comparative Results

The FLOT QA algorithms were tested using problems presented by Nugent, Vollmann, and Ruml (1968).[2] These problems have been used as benchmarks for comparing QA solution procedures, in terms of solution quality and computation time, since 1968. There are eight problems, ranging in size from 5 to 30 workstations, with five starting solutions for each problem.

The test runs were performed on an IBM 4381. Table B-1 presents the cost of the final solution found by each of the seven heuristic algorithms for each starting solution of the eight problems. Table B-2 presents the average final cost of the five starting solutions for each of the eight problems found by each heuristic algorithm. Table B-3 presents average computer time used to solve each of the five starting solutions for each problem. Table B-3 includes enumeration; however, solving the 12 workstation and larger problems by enumeration was not computationally feasible.

Discussion of Results

To test for differences in performance of solution algorithms and to test the significance of problem size to solution variability, an analysis of variance (ANOVA) was performed. The dependent variable is the cost (measure of quality) difference between the cost of the final solution and the best solution. The solution algorithm is a fixed independent variable, the problem size is a random independent variable, and the starting solution is a random independent variable nested in the problem size. An alpha (a) of 0.05 was chosen to determine significance. The results of the ANOVA calculations are presented in Table B-4.

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[2]FLOT has also been tested on numerous hypothetical command post arrangements as well as on problems generated during an analysis of data from Michel & Fallesen (1990) related to alternate battalion task force command post arrangements.

Table B-1

Final Costs From the Seven Heuristic Algorithms for the Nugent et al. (1968), Test Problems

Number of facilities	Starting solution	Best known solution	Starting solution value	Heuristic algorithms						
				COL	TSP	MTSP	CRAFT2	CRAFT2-3	STEEP3-2	CRAFT-32
5	1	25	33	29	29	29	29	29	29	29
	2		29	29	29	29	29	29	29	29
	3		36	25	25	25	25	25	25	25
	4		34	29	29	29	29	29	29	29
	5		41	29	29	29	29	29	26	29
6	1	43	43	43	43	43	43	43	43	43
	2		55	43	43	43	43	43	46	46
	3		54	46	46	46	46	46	46	46
	4		58	43	43	43	43	43	43	43
	5		58	46	46	43	46	46	46	46
7	1	74	87	76	76	76	79	79	76	76
	2		120	78	78	78	78	78	79	78
	3		108	74	74	74	74	74	74	74
	4		114	74	74	74	84	79	75	75
	5		101	83	83	83	83	78	76	76
8	1	107	136	107	107	107	119	119	113	113
	2		161	116	116	107	107	107	107	107
	3		145	124	124	124	124	120	107	107
	4		160	110	110	110	110	107	111	107
	5		144	109	109	109	107	107	107	107
12	1	289	392	298	300	298	298	298	307	307
	2		392	308	308	308	308	298	300	293
	3		437	317	303	326	291	291	298	298
	4		425	305	305	305	295	295	293	295
	5		373	311	311	305	289	289	311	311

Table B-1 (continued)

Number of facilities	Starting solution	Best known solution	Starting solution value	Heuristic algorithms						
				COL	TSP	MTSP	CRAFT2	CRAFT2-3	STEEP3-2	CRAFT-32
15	1	575	724	629	633	628	628	627	578	578
	2		806	603	588	593	606	594	588	595
	3		798	607	607	607	591	591	596	602
	4		805	603	608	608	640	621	575	575
	5		813	585	599	600	583	583	597	597
20	1	1285	1722	1330	1325	1342	1338	1338	1326	1334
	2		1651	1345	1340	1350	1354	1349	1320	1339
	3		1770	1309	1342	1344	1351	1298	1325	1325
	4		1728	1329	1304	1304	1324	1324	1366	1367
	5		1661	1328	1342	1321	1332	1326	1324	1324
30	1	3062	4030	3159	3163	3150	3090	3090	3134	3134
	2		3879	3238	3155	3186	3159	3159	3113	3219
	3		4086	3225	3184	3226	3197	3197	3173	3107
	4		3824	3183	3227	3203	3273	3205	3144	3144
	5		4112	3224	3181	3193	3237	3200	3142	3139

Table B-2

Average Final Cost Reached by Each Heuristic Algorithm for the Five Starting Solutions of the Problems Presented by Nugent et al. (1968)

Number of facilities	COL	TSP	MTSP	CRAFT2	CRAFT2-3	STEEP3-2	CRAFT-32
5	28.2	28.2	28.2	28.2	28.2	27.6	28.2
6	44.2	44.2	43.5	44.2	44.2	44.8	44.8
7	77.0	77.0	77.0	79.6	77.6	76.0	75.8
8	113.2	113.2	111.4	113.4	112.0	109.0	108.2
12	307.8	305.4	308.4	296.2	294.2	301.8	300.8
15	605.4	607.0	607.2	609.6	603.2	586.8	589.4
20	1328.2	1330.6	1332.2	1339.8	1327.0	1332.2	1337.8
30	3205.8	3182.0	3191.6	3191.2	3170.2	3141.2	3148.6

Table B-3

Average Seconds of IBM 4381 Time Used to Solve Each of the Five Starting Solutions for the Problems Presented by Nugent et al. (1968)

Number of facilities	Enumeration	COL	TSP	MTSP	CRAFT2	CRAFT2-3	STEEP3-2	CRAFT-32
5	0.16	0.11	0.12	0.12	0.11	0.11	0.12	0.12
6	0.36	0.13	0.12	0.12	0.12	0.12	0.14	0.12
7	2.29	0.12	0.12	0.13	0.12	0.14	0.19	0.17
8	22.76	0.13	0.14	0.14	0.14	0.17	0.24	0.25
12	--	0.18	0.22	0.23	0.29	0.49	1.27	1.16
15	--	0.29	0.40	0.36	0.52	1.32	3.79	4.14
20	--	0.61	1.19	1.27	1.48	4.60	17.09	15.69
30	--	1.96	6.40	6.43	8.55	25.56	170.50	168.20

Table B-4

The ANOVA Results[3]

Summary of all Effects
1 - Solution Algorithm, 2 - Problem Size, 3 - Starting Solution

Effect	df effect	MS effect	df error	MS error	F	p-level
1	6	814.71	42	390.23	2.088	.075007
*2	7	52284.43	32	715.79	73.016	.0000001
3	32	715.79	---	---	---	---
*12	42	390.23	192	232.63	1.677	.010462
13	192	232.63	---	---	---	---

* Marks effects that are significant at $p \leq .0500$

The solution algorithm ($F(6,42)=2.09$, $p<0.075$) was not significant. The problem size ($F(7,32)=73.02$, $p<0.000001$) was significant and the largest predictor of solution variability. The interaction between solution algorithm and problem size ($F(42,192)=1.68$, $p<0.01$) was significant.

Post hoc comparisons of the problem size were not possible because the problem size is a random variable. However, based on observations of the results, the variation of the final solution cost from the cost of the best solution increases as the size of the problem (number of stations) increases.

The mean of the differences between the value of the best known solution and the algorithm's solutions for each algorithm can provide a rank ordering of the best to the poorest solution algorithm, as presented in Table B-5. The reader is cautioned that the rank ordering does not consider variability or statistical significance.

[3] The unbiased test for the solution algorithm (1) effect is to use the mean square of the algorithm and problem size interaction (12) as the error term. Similarly for the problem size (2) effect an unbiased test uses the mean square of the starting solution within problem size (3) as the source of error. The unbiased test for the interaction between the solution algorithm and the problem size (12) uses the algorithm and starting solution interaction (13) mean square as the error term. Neither the starting solution (3) nor the interaction between the solution algorithm and the starting solution (13) could be tested.

Table B-5

Rank Ordering of Mean Differences from the Best Solution

Algorithm	Mean difference
Steep3-2	19.925
CRAFT-32	21.700
CRAFT2-3	24.575
TSP	28.450
MTSP	29.950
CRAFT-2	30.275
COL	31.225

Depending on the problem and the starting solution, each solution algorithm found a solution that was superior to the solution found by the other algorithms for that starting solution at least once. The Steep3-2, followed closely by CRAFT-32 and CRAFT2-3, found the superior solution more times than the other algorithms did. However, for the first starting solution of the 12 workstation problem (see Table B-1), COL, MTSP, CRAFT-2, and CRAFT2-3 found the superior solution, and only CRAFT-2 and CRAFT2-3 found the best known solution for the 12 workstation problem. This was found when using the fifth stating solution. In the 20 workstation problem, the TSP found the superior solution on the first starting solution and the MTSP found the superior solution on the fifth starting solution.

When considering Table B-1, one has to bear in mind that the best known solutions have been found during long periods of testing with different methods and different starting solutions. Hitchings and Cottam (1976) showed that by changing one selection and exchange decision made when using the TSP, on the 30 workstation problem, with the fourth starting solution, the final solution found had a value of 3086. The one changed decision was to select the other exchange, of two possible exchanges that offered the same potential improvement (a tie), in the 32nd iteration (more than 60 iterations were needed to reach a final solution).

Table B-3 confirms that COL algorithm is the fastest algorithm, followed by TSP, CRAFT, and 3-way exchange algorithms. This table also shows that Steep3-2 and CRAFT-32 require increasing amounts of computation time to solve larger problems. This suggests that Steep3-2 or CRAFT-32 may not be feasible to use when solving 50 to 100 workstation QA problems, depending on the computer resources available and the time allowed for the analysis.

Conclusions

For large problems (more than 10 workstations), no one algorithm proved to be able to find better solutions than the other algorithms during all circumstances. Each heuristic algorithm in this study provided a better solution than did the other heuristic algorithms at least once (see Table B-1), depending on the problem size and the starting solution. This observation suggests that to find the best solution, the user should use as many different heuristic algorithms and starting solutions as possible in the time available for the analysis.

The current version of FLOT uses a random solution generator for generating different starting solutions. Solving different starting solutions with a heuristic algorithm will increase the quality of the best solution found, or at least it will increase confidence that the best solution found is close to the optimal.

The default algorithm selections (based on average solution quality and speed) that are made by FLOT are as follow:

Number of Workstations	Algorithm
9 or fewer	Enumeration
10 to 15	Steep3-2
16 to 25	CRAFT2-3
26 or more	COL

These default selections will yield, in a small amount of computer time, reasonably good quality solutions. By using the default selection and a random starting solution generator better quality solutions, or at least more confidence in the quality of a best solution, can be obtained.

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